TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

ARTO HUUSKONEN

INCLUSION OF OCCUPATIONAL SAFETY IN LIFE CYCLE ASSESSMENT

Master of Science Thesis

Examiner: Professor Kaija Leena Saarela
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Abstract

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Products and services are affecting human health through more ways than one. Some of the impacts on human health are well known while others have not been paid much attention to. This study determines the impacts of occupational safety and environmental releases associated with the entire life time of a waste gasification plant on human health. The need for a study of occupational safety from a life cycle perspective has been often highlighted, but only a handful of studies have been carried out to date.

This study is carried out using life cycle assessment for identifying, compiling and assessing all relevant impacts on human health. The environmental impacts are assessed using Eco-Indicator 99 methodology. For occupational impacts a methodology has been developed based on the ones described in literature. The methodology development is reported as a part of this study. The environmental and occupational health impacts are combined to determine whether or not occupational accidents are a major cause of human health impacts, and also if there is a risk of trade-offs between environmental and occupational health impacts.

The outcomes of this study show that the occupational accidents have a relatively small impact on human health. Instead, the vast majority of human health impacts are caused by the release of emissions to air. The human health impacts can therefore best be reduced by improving the environmental performance of products. On the other hand the results of this study show that the majority of environmental and occupational health impacts arise from different processes. Therefore the improvements in the environmental performance of products do not necessarily lead to improvement in occupational safety. On the contrary, there is a severe risk of increasing the occupational health impacts as a result of striving exclusively towards better environmental performance.

The study of occupational safety as a part of life cycle assessment studies is essential to ensure that the decisions made based on their outcomes take all relevant issues into consideration. The method used in this study is however not sufficiently accurate to serve as a stand-alone tool. The method is affected by a number of potential sources of error and has to be further developed or used together with more accurate and narrow-scoped tools such as risk assessments.

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Tuotteet vaikuttavat ihmisten terveyteen usealla eri tavalla. Jotkin vaikutuksista ovat hyvin tunnettuja, kun taas toisiin ei ole kiinnitetty juurikaan huomiota. Tässä tutkimuksessa tarkastellaan työturvallisuuden ja ympäristöön kohdistuvien päästöjen vaikutuksia ihmisten terveyteen jätteenkaasutuslaitoksen osalta sen koko elinkaaren ajalta. Työturvallisuuden tarkastelemisen tärkeyttä elinkaarinäkökulmasta on korostettu moneen otteeseen, mutta aiheeseen liittyviä tutkimuksia on julkaistu vain muutamia.

Tämä tutkimus on toteutettu elinkaariarvioinnin pohjalta. Ympäristövaikutukset on arvioitu käyttäen Eco-Indicator 99 –metodologiaa terveysvaikutusten määrittämiseksi. Erillinen menetelmä on kehitetty työturvallisuudesta aiheutuvien terveysvaikutusten määrittämiseksi. Menetelmän kehitystyö on kuvattu osana diplomityötä. Ympäristövaikutukset ja työturvallisuuden vaikutukset on koostettu yhteen sen arvioimiseksi, ovatko työtapaturmat merkittävä terveysvaikutusten lähde ja onko niiden ja ympäristövaikutusten välillä olemassa kuormituksen siirtymisen riski.

Tutkimuksen tulokset osoittavat, että työturvallisuudella on suhteessa vain pieni merkitys ihmisten terveyden kannalta. Suurin osa terveysvaikutuksista aiheutuu sen sijaan ilmakehään kohdistuvista päästöistä. Tästä johtuen terveysvaikutuksia voidaan tehokkaimmin vähentää pienentämällä tuotteiden ympäristökuormitusta. Toisaalta tutkimuksen tulokset osoittavat, että työturvallisuudesta ja ympäristöpäästöistä syntyvät terveysvaikutukset aiheutuvat pääosin eri prosesseista. Tästä johtuen tuotteiden ympäristösuorituskyvyn parannukset eivät johda välttämättä parantuneeseen työturvallisuuteen. On olemassa jopa huomattava riski työturvallisuuden huononemiselle pyrittäessä yksinomaan kohti parempaa ympäristösuorituskykyä.

Työturvallisuuden tarkasteleminen elinkaariarvioinnin osana on välttämätöntä jotta voidaan varmistaa päätöksenteossa otettavan kaikki oleelliset tekijät huomioon. Tässä tutkimuksessa käytetty menetelmä ei kuitenkaan ole tarpeeksi tarkka toimiakseen yksittäisenä työkaluna. Menetelmään kohdistuu useita mahdollisia virhelähteitä, ja sitä tuleekin kehittää edelleen tai käyttää yhdessä tarkempien ja rajatumpien työkalujen kuten riskien arvioinnin kanssa.

Preface

In summer of 2010 I received the position as a summer trainee in Metso Power’s HSE department. One of the tasks that were handed to me was to participate in Metso’s recently started life cycle assessment (LCA) pilot project. The pilot project also marked the beginning of my journey with LCA. As the summer and my job as a summer trainee came to its end, the journey with LCA continued.

Now, two years after my first real touch with life cycle assessment, I am working for Metso Corporation as a life cycle assessment specialist. In the mean time I have had the honor of participating in numerous interesting projects which have also helped me in preparing two LCA related theses. This paper marks the closing of one cycle as I have returned to work with Metso Power in preparing my third and final thesis for my Master of Science studies at Tampere University of Technology.

The first idea of studying occupational safety as a part of LCA emerged about one year ago. Since then the idea slowly matured to the point where it became the subject of my Master of Science thesis. A number of people are to thank for that and also for their other efforts supporting my work, including for example Tuomo Kallioniemi from Metso Power, Marke Kallio from Metso Mining and Construction and Sari Pasanen from Metso Automation. Foremost to thank are Anita Korvenoja from Metso Power, Linnea Peltonen from Metso Corporation and Kaija Leena Saarela from Tampere University of Technology for their great feedback and advices related to this and other projects.

Special thanks for the completion of this thesis go to my wife Anna, who has been continuously pushing me towards graduation. She has done a remarkable job as a personal study counselor and motivator, and it is by no means an overstatement to say that this thesis would have taken twice as long to write if she weren’t there.

Finally, as all of my work and also this thesis are closely associated with sustainable development, it is important to have an idea of whose safe future we must secure. This idea is provided to me by Otso and Jaako, who have shown me both the fragility and resilience of life. For that I own more to them than they could ever own me for anything I do.

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Symbols and abbreviations

Mathematical symbols

$\bar{A}_{s,y}$	Average life expectancy at the time of occupational or commuting accident according to the age and sex of injured worker
Cf	Characterization factor expressing the impacts on human health resulting from fatal occupational or commuting accidents
Cnf	Characterization factor expressing the impacts on human health resulting from non-fatal occupational or commuting accidents
$DALY$	Disability adjusted life year: a unit expressing one lost year of "healthy" life. DALYs are calculated as the sum of the Years of Life Lost (YLL) and the Years Lost due to Disability (YLD)
DQR	Data quality rating for life cycle inventory datasets
DW_i	Disability weight expressing the severity of given medical condition resulting from occupational or commuting accident
$\dot{FA}$	Accident frequency for fatal occupational accidents
$\dot{FAC}$	Accident frequency for fatal commuting accidents
I	Incidence of occupational or commuting accidents resulting in a given medical condition
k_y	Correction factor for calculating the amount of non-fatal accidents covering also accidents that lead to less than four days absence from work and that have therefore not been included in the accident statistics
L_d	Average duration (healing time) of given medical condition resulting from occupational or commuting accident
L_f	Average life expectancy at the time of fatal occupational or commuting accident
N	Number of fatalities associated with occupational or commuting accidents
$N_{s,y}$	Number of fatalities associated with occupational or commuting accidents according to the age and sex of fatally injured workers
$\dot{NFA}$	Corrected accident frequency for non-fatal occupational accidents
$\dot{nfa}$	Reported accident frequency for non-fatal occupational accidents (including only accidents leading to at least four days away from work)
$\dot{NFAC}$	Corrected accident frequency for non-fatal commuting accidents
$R_{a,c}$	Average rate of occupational accidents in a specific country
$R_{a,RE}$	Average rate of occupational accidents in a reference geographical area
YLD	Years lost due to disability: a unit expressing one lost year of "healthy" life due to disability caused by illness or accident. The LYD is calculated by multiplying the

number of incidents with their disability factors and durations

YLL Years of life lost: a unit expressing one lost year of life due to premature death. The YLL is calculated by multiplying the number of deaths by the standard life expectancy at the age at which death occurs

WH_c Average annual working time in a specific country

WH_i Overall working time for a specific industry sector during a reference period of time

WH_{RE} Average annual working time in a reference geographical area

WH_y Average annual working time during a reference year (in a specific geographical area)

Abbreviations

APC Air pollution control residue: all incineration and flue gas cleaning residues that are collected from the incineration process after the boiler and economizer

BAT Best available technique: set of most advanced technically and economically feasible techniques for the prevention of contamination of environment and the reduction of environmental impacts

CHP Combined heat and power: the use of a power station for simultaneous generation of heat and electricity

(E)LCA Environmental life cycle assessment: see LCA

GHG Greenhouse gas: gas that allows sunlight to enter the Earth's atmosphere but absorbs infrared radiation reflected by Earth's surface. Over time, the absorbed energy raises the temperature of the atmosphere causing global warming

FA Fatal occupational accident: an occupational accident leading to death

FCA Fatal commuting accident: a commuting accident leading to death

HSE Health, safety and environment: the management of occupational health and safety issues and environmental issues in companies

HWI Hazardous waste incineration: thermal treatment of hazardous waste with the purpose of reducing the overall environmental impact that might otherwise arise from the waste

LCA Life cycle assessment: a standardized environmental assessment method the purpose of which is to compile and evaluate the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. Also referred to as environmental life cycle assessment ((E)LCA).

LCI Life cycle inventory analysis: phase of life cycle assessment which involves the compilation and quantification of inputs and outputs of a product system throughout its life cycle

LCIA Life cycle impact assessment: phase of life cycle assessment during which the magnitude and significance of the potential environmental impacts of a product system will be evaluated throughout its life cycle

LCM Life cycle management: a business management concept, the purpose of which is to minimize environmental burdens throughout the life cycle of a product or service

LCT Life cycle thinking: thinking approach which aims to identify possible improvements to product systems in the form of lower environmental impacts and/or increased environmental benefits across all life cycle stages

MSWI — Municipal solid waste incineration: thermal treatment of municipal solid waste with the purpose of reducing the overall environmental impact that might otherwise arise from the waste

NFA — Non fatal occupational accident: an occupational accident that leads to temporary or permanent medical condition

NFCA — Non fatal commuting accident: a commuting accident that leads to temporary or permanent medical condition

PM — Particulate matter: emissions to air consisting of solid particles. Grouped to three categories (PM>10, PM2,5-10 and PM<2,5) according to the diameter of particles

RA — Risk assessment: a systematic process of evaluating the probability and impacts of events that could affect the achievement of objectives

REF — Recycled fuel: fuel produced of separately collected burnable waste from municipalities and companies. REF is classified to three categories (I-III) according to its chemical composition and energy content

SLCA — Social life cycle assessment: an assessment method the purpose of which is to compile and evaluate the potential social impacts of a product system throughout its life cycle

1 Introduction

The interest towards the environmental impacts of products arose strongly in the late 1960s and early 1970s following the concern over the depletion of energy and raw material resources. Tools for assessing the environmental impacts of products were developed following the increased interest and used to support environmentally sound decision making. In the beginning the emphasis was mainly on studying energy use of some specific parts of product life cycle and identifying means for reducing it. The scope was later expanded to cover also other important issues and parts of product life cycle. The coverage was however tightly limited to more or less traditional environmental issues, while the other aspects of sustainability were left beyond the scope of the tools. (Curran 2006)

The development of environmental assessment methods culminated with the standardization of Life cycle assessment (LCA) by ISO in the late 90s, which is to date the only internationally standardized environmental assessment method (Curran 2006). LCA has been defined as a tool for assessing all "*potential environmental impacts of a product system*" (ISO 14040; ISO 14044). What is considered environmental impact has however not been defined, and the door has been left open for the types of impacts that have yet to be identified or considered worthwhile studying. Still, the focus has been firmly on environmental impacts, and it has therefore been clear from the very get-go that LCA alone is not a sufficient metrics for assessing the sustainability of products (Klöpffer 2008). The exclusion of other than environmental impacts has even been considered a major threat to the purpose of LCA: LCA is used to support life cycle thinking, the purpose of which is to avoid shifting burdens from one part of the product system or one type of environmental impact to another. If LCA is focused only on studying environmental impacts, burden can be shifted from one aspect of sustainability to another thus making it that no real benefits are necessarily gained (Hellweg et al. 2005; Reap et al. 2008; Pettersen & Hertwich 2008; Hofstetter & Norris 2003; Kim & Hur 2009).

Lately a lot of attention has been focused on expanding the LCA framework to cover also other aspects of sustainability. UNEP published the guidelines on social life cycle assessment (SLCA) in 2009 and ISO is working to develop standards to support life cycle costing (LCC). A number of case studies have been published, some of which have indicated that there really is a risk of shifting burdens from one aspect of sustainability to another. In the mean time LCA has also become less of a purely scientific tool but more of a tool for supporting decision making in companies and politics. The history of LCA has however unfortunately shown that while a lot of work has been focused on developing LCA as a scientific method, the practical applications and the ease-of-use of the tool have been sometimes forgotten. To avoid these problems, it is important that all of the users of LCA and related tools are heavily involved in their development to ensure that the tool is not only valid, but also practical.

This was also one of the major findings of Metso’s LCA pilot project, which was carried out in 2010-2011 in four different Metso’s business lines. Metso is an international company operating in power, pulp, paper, mining and oil industries. The company has a range of products varying from small automation components to complete pulp mills. LCA was identified to offer Metso with a range of benefits during the pilot project, but the lack of its flexibility was from time to time causing the cons to overcome the pros. Also the fact that LCA is limited to environmental impacts only is one of its drawbacks: as Metso is heavily committed to providing sustainable products, they must be ensured to be sustainable from all perspectives and not just regarding environmental impacts.

An aspect of product sustainability that has gained particular interest of many industrial and scientific users of LCA is occupational health and safety. Occupational health and safety issues and environmental issues are commonly managed and supported by the same group of people in companies. They are known to pose a lot of synergies and common concerns. Still, they are only rarely assessed using common tools, at least from the product perspective. So far a group of scientific users of LCA have demonstrated that there is a clear need for using common metrics, and that the development of such metrics is at least theoretically possible. (e.g. Hofstetter & Norris 2003)

In order to determine whether or not such tools are practically feasible to be used and can be used to support decision making, the industrial users, i.e. the ones who are making the decisions, have to step into. The fact that Metso is strongly committed to being the leading star in occupational health and safety as well as environmental issues, and that Metso is operating in businesses where all of these are fundamental aspects of companies’ performance make it that there is a strong opening for the company to test these methods at a very early point. The early involvement also makes it that Metso can contribute to the methodology development and in this way ensure that the development is heading the right way.

The purpose of this master’s thesis is to serve as a test piece in determining if the combined study of occupational health, safety and environment from product perspective is a path Metso can take. The study is done in collaboration by Metso Corporation and Metso Power business line, which is a leading provider of various biomass solutions for energy generation. The applied part of this study consists of two parts. In the first part the available methods are compared and assessed to determine if they are applicable for Metso Power. If necessary, an applicable method will be developed based on some of the existing methods.

The second part is a case study testing the practical applicability of one method that has been considered most promising.

The case study will be done so to support an ongoing life cycle assessment of a waste gasification plant. This brings many benefits as the same data can be utilized in both studies. However, the fact that the studied product is a newly developed and unique solution also makes it that the data collection can for some parts be challenging and sets some limitations on the reporting of data. Also the fact that the study deals with a waste incineration system requires the careful consideration of numerous aspects of LCA. The issues that need to be taken into consideration will be reviewed as a part of the theory section of this thesis.

2 Theoretical backgrounds

2.1 Life cycle assessment

2.1.1 LCA framework and applications

Life cycle assessment (LCA, also referred to as environmental life cycle assessment, (E)LCA) is an internationally standardized method for compiling and evaluating all inputs and putouts as well as potential environmental impacts of a product system throughout its entire life time. LCA covers both direct and indirect environmental impacts and is not limited to the study of a single impact category, such as global warming. LCA is a relative method and does not provide one with information about risks or acceptable impacts. Furthermore, LCA does not provide one with information about actual environmental impacts taking place in a given place at a given time. (ISO 14040; European Commission 2010a)

LCA can be used for a number of purposes either within the commissioning organization or externally in the communication between the organization and its interest groups. LCA results are commonly used in business strategy, research and development, product or process design, policy development, environmental labeling, sales and procurement. According to Frankl and Rubik (1999), the most important applications include weak-point analysis of products and external communications. (ISO 14040; Cooper & Fava 2006)

The motivators for carrying out LCA studies can be divided into process, image and compliance-oriented drivers. Process-oriented drivers are commonly the most important ones aiming at cost, material and energy savings. Image-oriented drivers on the other hand emphasize the communication between organizations and their interest groups and ultimately aim at creating new market openings and maintaining existing ones. Compliance-oriented drivers then again aim at preparing the organization for future changes in the legislator framework. (Nygren & Antikainen 2010, pp. 13)

LCAs are carried out for both new and existing products. The assessments do not usually cover all products, but only selected ones. This can be considered to be due to the complexity of the method and the resulting limitations in its applicability. (Cooper & Fava 2006; Frankl & Rubik 1999)

2.1.2 Progress of an LCA study

LCA is divided into four parts in the ISO standards as illustrated in figure 2.1. All of the parts that make up an LCA study have been described in the ISO standards 14040 and 14044. The general idea is to start the assessment with the definition of the goals and scope of the study, then move on to data collection and later assessment of the environmental impacts. Outcomes of each step as well as their impacts on the proceeding and preceding steps should be interpreted as the study progresses in order to ensure that the goals of the study and the requirements of the applicable standards are met. (ISO 14040; ISO 14044)

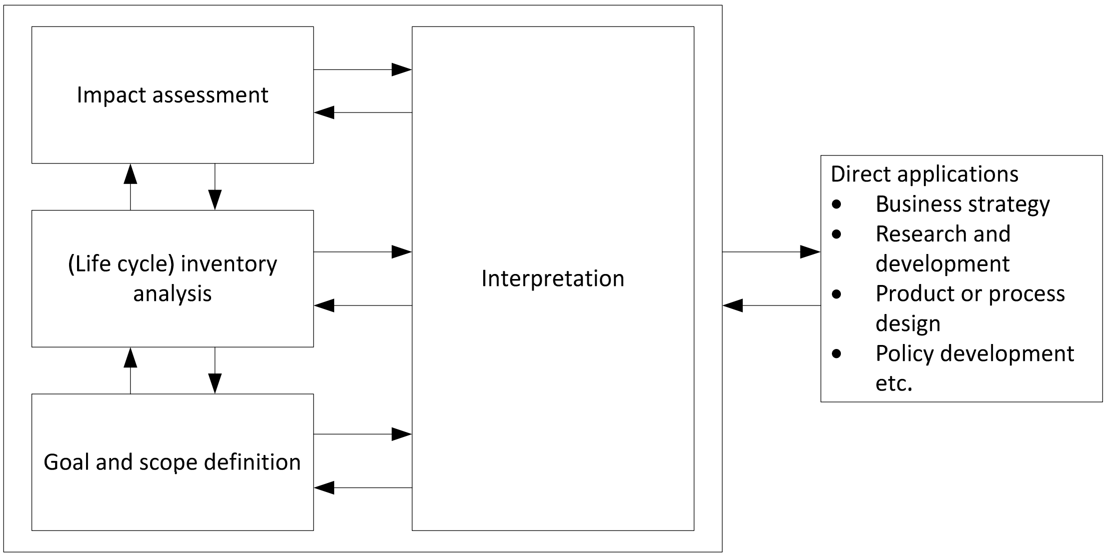

Figure 2.1. *Stages of an LCA process and their interactions (ISO 14040)*

The LCA process is iterative, and preceding phases are returned to during the course of the study if necessary. The iterative approach can both improve the accuracy of LCA studies as well as reduce the associated work load. In practice the iterative approach means that the assessments are started with easily available data. The important aspects are then identified based on the initial data and more accurate (and harder to get) data is then collected for the relevant parts. Each iteration should consider not only the results of the inventory analysis, but also the outcomes of goal and scope definition and impact assessment. A general idea of the iterative approach to LCA is illustrated in figure 2.2. (ISO 14040; European Commission 2010a, pp. 25-28)

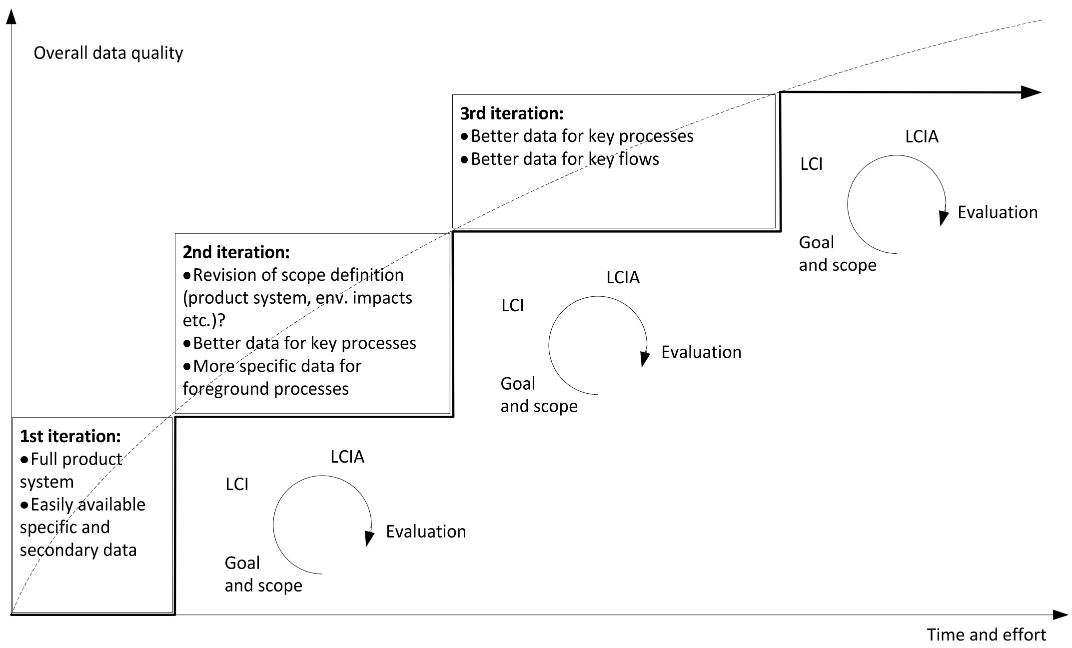

Figure 2.2. *Iterative approach to LCA (European Commission 2010a, pp. 25)*

2.1.2.1 Goal and scope definition

The purpose of goal and scope definition is to determine the reasons for carrying out the study and the product system that will be studied. Both the goals and the scope of the study have to be in line with the intended applications of the study: in case the study is for example intended to support ecodesign, is should cover all relevant stages of product life cycle as well as all relevant environmental impact categories and not just for example greenhouse gas emissions. (ISO 14044; ISO/TR 14062)

The goal and scope definition includes among other the definition of functional unit and reference flow. Functional unit is the quantified performance of the product system. Based on the functional unit, a reference flow is formed. Reference flow forms the basis for normalizing the input and output data. (ISO 14044)

Also the system boundaries have to be defined during the goal and scope definition. System boundaries determine which unit processes are included in the assessment. All unit processes related to the operation of the studied system should be included in the study, unless their exclusion does not have an impact on the outcomes of the study. When studying completely new products, this can in most cases be determined only by trying to incorporate all processes, and exclude them from the final assessment in case their contribution to the overall environmental impacts is irrelevant. (ISO 14040; European Commission 2010a, pp. 93-108)

The decision over the studied environmental impacts has to also be made during the goal and scope definition. The decision again has to be in line with the intended applications of the study.

An important factor regarding the validity and accuracy of the results is the accuracy and validity of inventory data. The goal and scope definition should therefore include data quality requirements that are set for the inventory analysis, data sources that are used as well as calculation procedures used for calculating the inventory data.

Finally, goal and scope definition should take stand on the type of report published, and to whom it is intended to be communicated. In line with the intended audience and applications of the study, a decision over critical review of the study has to be made. Critical review is an assurance method for making sure that the study is done in a transparent and reliable way, and meets the requirements of the applicable standards. Critical review is voluntary except if the study is intended to support comparative assertions disclosed to public, in which case it is mandatory.

2.1.2.2 Life cycle inventory analysis

The purpose of life cycle inventory analysis is to collect, compile and quantify data regarding all inputs and outputs of the studied product system throughout its life cycle. Besides quantified data, also qualitative data (regarding e.g. geographical locations and utilized technologies) should be collected to support both the ongoing inventory analysis and the impact assessment. (ISO 14040; ISO 14044)

According to ISO 14044, the inventory analysis is characterized by a seven step procedure illustrated in figure 2.3. Basis for the inventory analysis is created during the goal and scope definition, which should determine data quality requirements, general calculation procedures and scope of the study. Of the general calculation procedures especially allocation should be paid close attention to. Allocation refers to the process of partitioning the inputs and outputs of a process or a product system between one or more products. Allocation should be primarily based on the underlying physical relationships of the products. However, in some cases these are hard to identify while in some cases numerous physical relationships can be identified. (ISO 14044)

Inventory analysis is commonly done partially by hand and partially using dedicated LCA software. LCA software such as GaBi and SimaPro are useful in collecting data and in relating the data to unit processes and functional unit. Some software include individual data modules or extensive LCI databases containing readily collected data regarding the inputs and outputs of common industrial processes.

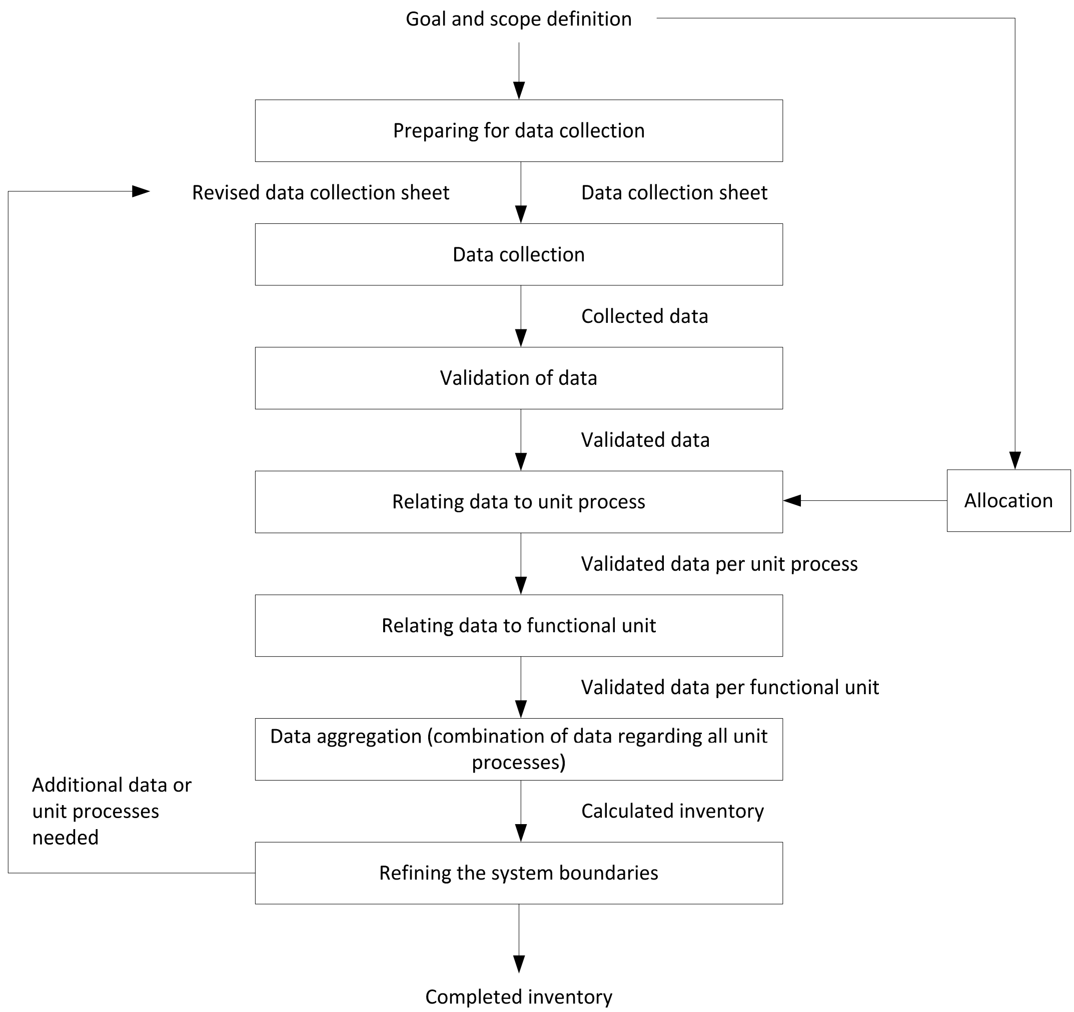

Figure 2.3. *General life cycle inventory analysis procedure (ISO 14044)*

The life cycle inventory analysis is in most cases the most time consuming part of LCA (Rebitzer et al. 2004; Cooper & Fava 2006). To minimize the data collection procedure, many parts of the studied systems are commonly modeled based on average data given in LCI databases and literature (Nygren & Antikainen 2010, pp. 15; European Commission 2010a, pp. 96-99, 190; Cooper & Fava 2006). Using data from LCI databases and literature is an efficient way of reducing the workload required to carry out an LCA study (Lewandowska et al. 2008). The use of average data however decreases the accuracy of the results, and the most important parts of the product system should therefore be studied based on case specific data.

The division of the studied system to foreground and background processes is helpful in determining which parts should be modeled based on case specific marginal data and which can be modeled using average data from literature and databases (Clift et al. 2000; Curran 2006, pp. 9-10; European Commission 2010a, pp. 96-99, 190). Two approaches can be used in defining the distinction between foreground and background systems (European Commission 2010a, pp. 96-99):

- **Specificity perspective:** processes specific to the studied system are a part of the foreground system. Processes for which a relatively homogenous market can be assumed to appropriately represent them are a part of the background system.
- **Management perspective:** processes that are directly under the control of the producer of the studied good (or operator of the studied service), or where the producer has significant influence, form the foreground system. Background system consists of the processes, regarding which the producer has no direct control or decisive influence.

In both cases the background systems are commonly modeled based on average data, and foreground processes based on case specific data if possible (Clift et al. 2000; European Commission 2010a, pp. 96-99, 190; Curran 2006, pp. 9-10). However, in neither case clear distinction between foreground and background systems is always possible (European Commission 2010a, pp. 96-99). Also, literature data should always be critically analyzed, and if necessary and relevant regarding the outcomes of the study, modified to meet the boundary conditions of the studied product system or replaced by case specific data when possible (Lewandowska et al. 2008; European Commission 2010a).

2.1.2.3 Impact assessment

Impact assessment is defined in the ISO standards as the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product" (ISO 14040; ISO 14044). In practice this means calculating the environmental impacts based on aggregated inventory data.

Impact assessment consists of three mandatory and four optional elements. The mandatory elements are selection of impact categories, category indicators and characterization models; assignment of LCI results to the selected impact categories (classification); and calculation of category indicator results (characterization). The optional elements then again are normalization, grouping, weighting, and data quality analysis. (ISO 14044)

There are no requirements regarding the choice over studied impact categories in the ISO standards apart from the statement that LCA studies should cover all relevant environmental impacts. Impact assessment is usually carried out using existing impact assessment methods such as CML 2001, Impact 2002+ or Eco-Indicator (Cooper & Fava 2006). This basically eliminates the need for defining category indicators, classification rules and characterization models. In some cases the existing methods may not however be sufficient nor applicable to the study, and a new impact assessment method has to be developed (ISO 14044). In this case the definition of the method has to follow the procedure described in ISO 14044:

1. Identification of category endpoint(s)
2. Definition of the category indicator for given category endpoint(s)
3. Identification of appropriate (elementary) flows that can be assigned to the impact category
4. Identification of the characterization model and the characterization factors

Category endpoints are attributes or aspects of natural environment, human health, or resources (which form the three areas of protection, AoPs) that identify an environmental issue giving cause for concern. The category indicator can be defined anywhere along the environmental mechanism, i.e. the system of physical, chemical and biological processes linking the elementary flows to category endpoints. In general, choosing the indicator closer to endpoint makes the results more practical and therefore easier to understand. This at the same time increases the uncertainty of the study, as one has to take into account also the sensitivity of the category endpoints to the environmental mechanisms affecting it as well as the exposure to them. (ISO 14044; Baer et al. 2000)

The environmental mechanism is also the key for identifying appropriate elementary flows to be assigned to the impact category: in order to identify the appropriate elementary flows, one has to first identify the environmental mechanism and then the flows that may trigger it. Some elementary flows can trigger numerous environmental mechanisms. If this is the case, one has to be careful not to double count the emissions, especially if the elementary flow is converted to another from along the environmental mechanism.

The optional elements of LCIA support the interpretation of results. They are not required by the ISO standards, but can be helpful in improving the accuracy and usability of the LCIA results.

2.1.2.4 Interpretation

The interpretation step of an LCA study should cover the identification of significant issues (based on LCI and LCIA results); an evaluation considering completeness, sensitivity and consistency of the study; as well as conclusions, limitations, and recommendations. Also the appropriateness of the definitions of the studied product system and the limitations identified by the data quality have to be covered. Interpretation should be done so that it supports the goals of the study. (ISO 14044)

In general, the interpretation aims at both identifying any limitations and deficiencies of the study, and providing the kind of quantitative and qualitative data needed to fulfill the goals of the study. The identification of limitations and deficiencies is crucial to avoid drawing false conclusions based on the LCA study.

2.1.3 Benefits and limitations of LCA

According to Dalhammar (2007), life cycle oriented legislation should – among others – strive to avoid passing environmental problems from one part of the life cycle to another as well as avoid transferring pollution from one media to another. Such legislation should also stimulate cooperation among various actors in the supply chain and to involve them in continuous improvement to reduce life cycle impacts.

The statements presented by Dalhammar (2007) consider not only life cycle oriented legislation, but life cycle thinking (LCT) in general (United Nations Environment Programme 2004). Making decisions based on life cycle thinking then again requires life cycle management (LCM) (United Nations Environment Programme 2004). According to a fundamental management guideline, one can only manage what they measure. Life cycle management requires therefore the use of life cycle based metrics.

One of the core benefits of LCA is that it answers the questions that form the center of LCT and LCM. Identifying trade-offs and visualizing the impacts of supply chains is generally considered to be the major strengths of the LCA framework (e.g. ISO 14040; Curran 2006, pp. 3). LCA can for one help identify situations, where reducing the environmental impact of a given point source would increase the environmental impacts elsewhere and thus lead to an overall reduction in environmental impacts. LCA can also provide information regarding those parts of the product system that the commissioner of the study cannot directly measure.

It is also an inbuilt feature of the LCA framework that it enables the quantification of the product system's overall environmental impacts. This for one enables benchmarking of competing products and the identification of significant issues, which can then help for example product designers identify the key environmental parameters. (e.g. ISO 14040; Curran 2006; European Commission 2012)

LCA does on the other hand pose some major limitations that have to be considered before carrying out an LCA study, and when interpreting its results. A major issue limiting the use of LCA is its complexity and the resulting high time and resource intensity. These limitations can be partially solved by leaving selected parts of the product system outside of the system boundaries, using less sophisticated methods for the assessment (e.g. streamlined life cycle assessment) or by using average data for the analysis. The solutions however pose a trade-off between the accuracy of results and the workload associated with the study, and cannot be held a universal solution. (e.g. Antikainen 2010; Cooper & Fava 2006; Curran 2006; United Nations Environment Programme 2003)

Another limitation of the LCA framework is that it does not answer all relevant questions and that it is highly vulnerable to methodology and value choices (Finnveden 2000; Klöpffer 2008). LCA cannot for one be used to measure impacts at a given time in a given place (Ekvall et al. 2007; European Commission 2012). The results of an LCA study also depend on the methodological choices made during the progress of the study, and the results do not therefore provide one with an absolute truth (Finnveden 2000).

LCAs are also limited by deficiencies in the quality of data. In most cases LCAs deal with impacts taking place in the future and the studies are therefore based on models that are valid only under certain conditions. The quality of the inventory data is also a major issue that limits the accuracy of results. According to Finnveden and Lindfors (1998), the emissions reported in different life cycle inventories can differ from one another by factors up to 100. (Finnveden 2000)

A further limitation that has to be considered is the fact that no one study can provide one with universal statements. The results of a single LCA, as the results of any single study, can only provide one with hypotheses or theories. Furthermore, the results apply only under the given boundary conditions. To be apple to generalize the results, one has to therefore repeat the study under varying boundary conditions, and still no empirical proof can be obtained. According to Frankl and Rubik (1999), the fact that LCAs can result in differing results and conclusions is in fact the most common obstacle standing in the way of wider use of LCA. (Finnveden 2000)

Most of the limitations of LCA apply for many other system analysis tools as well, and should not be considered as a motivator for abandoning the LCA framework. Instead, the limitations have to be paid attention to in order to ensure the reliability and transparency of the study and to be able the get the most out of it. Even with all the limitations, LCA is a powerful method in answering the questions that fall in the applicable scope. (Finnveden 2000)

2.2 Social life cycle assessment

Social life cycle assessment (SLCA, also referred to as societal life cycle assessment) is an expansion of traditional LCA framework to consider also social impacts. Unlike in the case of LCA, there is no standardized method for SLCA. The United Nations Environment Programme has however published a guide on SLCA (United Nations Environment Programme 2009), which is at the moment the highest level of guidance in the field of assessing social impacts within LCA framework.

SLCA is built around the LCA framework and shares a number of common features. In both LCA and SLCA, the study focuses on product life cycle. The SLCA method is divided into four iterative steps (goal and scope definition, inventory analysis, impact assessment and interpretation of results) similar to the LCA. Impacts are assessed relative to functional unit and are well suited for identifying weak points and improvement potentials. (United Nations Environment Programme 2009, pp. 37-42; Benoît et al. 2010)

There are also a number of differences between the LCA and SLCA frameworks. While LCA focuses on process specific information, SLCA utilizes in many cases site, company or corporate level information. SLCA is also more sensitive to location specific boundary conditions, such as political attributes. SLCA is also more subjective method: many of the impacts are assessed through surveys and interviews, and represent therefore personal opinions rather than objective information. (United Nations Environment Programme 2009, pp. 37-42; Benoît et al. 2010)

Another difference between LCA and SLCA lies in the coverage of impact categories. While there are no strict guidelines for LCA on which impact categories to cover, the guidelines for SLCA contain a full list of impact categories that should be considered as a minimum. (United Nations Environment Programme 2009; Benoît et al. 2010)

The similarities between LCA and SLCA are not limited to the methodological framework. Also the difficulties faced by practitioners are in many cases similar. The inventory analysis is complicated and time consuming and can in some cases limit the usability of SLCA. Also comparisons of different products are problematic in both cases: in LCA the problems arise through different scopes and methods used in the assessment, while in SLCA also the subjectivity of the inventory data makes comparisons difficult. (Jørgensen et al. 2009: Benoît et al. 2010)

The availability of data and efforts related to its collection is something that is commonly considered a drawback of LCA (Cooper & Fava 2006). In the case of SLCA, this problem is further highlighted as the available databases are very limited. Furthermore, their usability can be questioned, since the social impacts are very much location specific, and since most LCA practitioners only rarely know the specific locations where the processes linked to the life cycle of their products take place (Benoît et al. 2010; Pennington et al. 2004). In fact, Jørgensen and colleagues (2009) conducted a survey on eight Danish companies aiming at determining the relevance and feasibility of SLCA from a company perspective. According to their findings, SLCA seems to be restricted to applications with very limited or no life cycle perspective due to the data availability issues. This then again limits the value of the tool, as it is specifically intended to support life cycle thinking. (Jørgensen et al. 2009: Benoît et al. 2010)

2.3 Simplified life cycle assessment

Cooper and Fava carried out an LCA practitioner survey in 2006, in which 65 LCA practitioners from around the globe shared their views on LCA. When asked what is keeping them from applying LCA more widely, three reasons were presented repeatedly: the collection of data takes too much time and resources, LCA method is complex, and there is no clarity on the business benefits of carrying out LCA studies.

Simplified LCA (also referred to as streamlined LCA) methods and approaches have been developed to overcome these limitations. Simplified LCAs are easier and faster to carry out, but the simplifications often come at the price of accuracy and coverage.

Simplified LCAs can therefore risk drawing false conclusions. (Antikainen 2010, pp. 19; Jensen et al. 1997, pp. 29-32)

Antikainen and colleagues (2012, pp. 37-40) have presented a series of general guidelines in choosing between simplified and full LCA. The intended audience, reasons for carrying out the study, level and detail of initial data, and the choices that can be made regarding the product system should be taken into account when making the decision. In practice, carrying out one full LCA creates a reliable basis for using simplified LCAs (Antikainen et al. 2012, pp. 37-40). Problems occur however, when LCA is used for product development: the efficient application of life cycle thinking requires that environmental impacts are paid attention to and assessed already during the product development, when very little data is available (ISO/TR 14062). Due to this, simplified LCAs are often resorted to even though all of the principles recommended by Antikainen and colleagues (2012, pp. 37-40) are not fulfilled.

Simplified LCAs consist of the same four steps as full LCAs. The simplifications can be done during all four steps: the scope of LCA can be limited to exclude some parts of product life cycle or some environmental impacts, case-specific data can be replaced by average data, and/or quantitative data can be replaced by qualitative data. (Antikainen 2010, pp. 19; Jensen et al. 1997, pp. 29-32)

As the simplification can affect the outcomes of the study, special attention should be paid to choosing the appropriate ways of simplifying the method without causing excessive loss of information. Jensen and colleagues (1997, pp. 29-32) recommend that simplification should be done in three iteratively linked steps:

1. **Screening**: Parts of product life cycle that are important or are not well known are identified
2. **Simplifying**: The results of the previous step are used to focus further work on the important parts of the product life cycle
3. **Assessing reliability**: It is checked that the simplifications made do not reduce the reliability of the overall results.

An extreme form of simplified LCA is the conceptual LCA described by Jensen and colleagues (1997, pp. 29-32). Conceptual LCA is based on the use of qualitative information, and the results are presented using qualitative statements. The term “conceptual LCA” has since been replaced by the term *life cycle thinking*, which indicates both the way of thinking behind LCA, but also the qualitative discussion aiming at finding the most environmentally significant parts of product life cycle. (Jensen et al. 1997, pp. 29-32)

Most of the LCA studies carried out today are somewhere between simplified LCAs and full LCAs (Antikainen 2010, pp. 19). In fact, many aspects of the procedure described by Jensen and colleagues (1997, pp. 29-32) have actually been embedded in the ILCD handbooks[1].

2.4 Application of life cycle based tools for decision making

Life cycle thinking is defined by the European Commission as a way of thinking seeking to "*identify possible improvements to goods and services in the form of lower environmental impacts and reduced use of resources across all life cycle stages*" (European Commission 2010g). Its main focus should not be on carrying out extensive and complicated environmental assessments, but rather in supporting decision making. As the detailed LCAs are often complicated and time consuming projects, they cannot be applied to all processes let alone all design concepts.

A lot of decision making concepts have been presented in order to enable a more flexible use of life cycle based information. They are usually based on the idea of using simple assessments and information whenever possible and resorting to more complex tools only when necessary. They usually combine both full and simplified LCAs. In many cases using detailed LCAs to support decision making is even impossible. The basic approach is therefore to use the simplest possible tools that enable the use of deficient and simple data in the beginning of a decision making process, and to resort to more sophisticated tools as the amount of detailed data increases. An example of this is illustrated in figure 2.4 for product development processes, and the same applies for other development and decision making processes as well.

[1] The ILCD handbooks published by the European Commission form a set of publications that aim to support the practical LCA work.

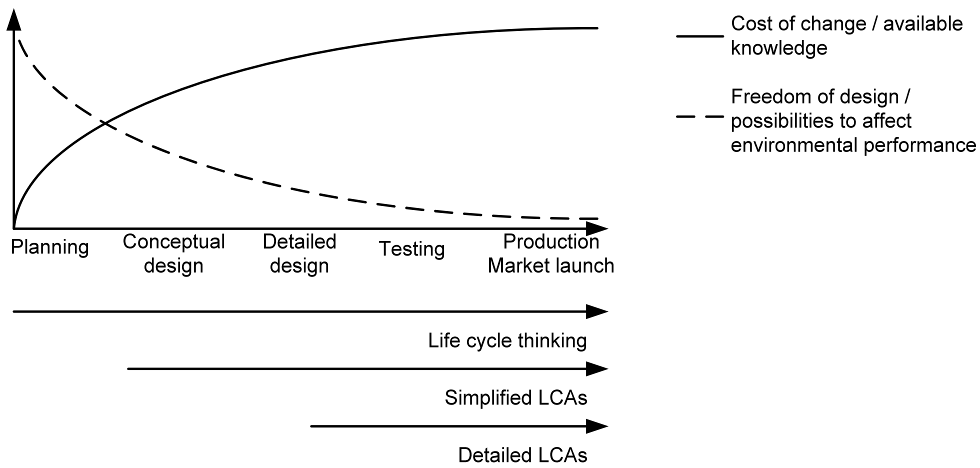

Figure 2.4. *A basic approach for using different life cycle based tools for product development (based on Metso's internal material)*

Life cycle thinking is based on existing information, which has to be acquired in some way. The information can be acquired from literature or through simplified or detailed LCAs (Antikainen et al. 2012, pp. 37-40). As the use of simplified tools often results in loss of information and therefore risks drawing false conclusions, they should be supported with more sophisticated tools when necessary (Antikainen 2010, pp. 19; Jensen et al. 1997, pp. 29-32).

2.5 Special consideration in LCAs of waste incineration systems

LCA has been often used as a decision supporting tool in analyzing different waste management strategies (e.g. Del Borghi et al. 2009; Gheewala 2009). A large amount of case studies have been published, many of which have focused on analyzing different waste management systems (mainly landfill, incineration and recycling). Also a number of scientific articles and guidebooks have been published that discus the special characteristics of using LCA for analyzing waste management systems. Still, a number of issues remain unsolved and many others require special attention.

For example Finnveden (1999) as well as Ekvall and colleagues (2007) discussed the deficiencies of using LCA for the assessment of waste management. Also Gheewala (2009), Baumann and Tillman (2004) and Sundqvist (1999) have discussed the challenges of using life cycle assessment to study different waste management approaches. According to their work, a number of open issues and challenges can be identified that are relevant for the study of waste incineration systems:

- System boundaries and functional unit

- Multifunctionality and allocation
- Time aspects and resulting challenges in impact assessment
- Spatial impacts
- Non-linear relationships
- Interpretation of field data and information on specific pollutants

The above listed issues are discussed briefly in this chapter. In addition to the specific limitations that LCA faces in the case of waste management, also a number of general limitations have to be taken into consideration. These include for example data quality issues, assessment of non-environmental impacts and the fact that LCA does not measure all relevant environmental impacts. These issues will also be briefly discussed in this chapter.

2.5.1 System boundaries and functional unit

In general, LCA should trace all inputs and outputs from “cradle” to “grave”, meaning that all inputs to the system should be inputs from nature rather than technosphere (ISO 14040; Finnveden 1999; Finnveden et al. 2005). In case of waste management this would then mean that all waste inputs should be traced up to the initial products and their production. This is however typically not done (Finnveden 1999). Instead, waste is treated as an input as it appears from its producer and the environmental impacts are calculated relative to a given amount of waste (Finnveden 1999; Ekvall et al. 2007).

The above mentioned approach does not contradict the definition of LCA if the input is similar in all compared systems (Finnveden 1999; Finnveden et al. 2005). However, the approach makes it impossible to analyze possible changes in the quantities of waste produced (Ekvall et al. 2007). It also makes it impossible to analyze the situation in a long run but is rather suited for analyzing what is the best solution for current situation (Ekvall et al. 2007).

The downstream system boundaries, i.e. the system boundaries for processes taking place in the value chain after the studied product have to be paid attention to as well in case some of the studied systems produce less waste than the others (Finnveden 1999). In case the amount and type of waste produced by all of the studied systems are identical, they can be left outside of the study. On the other hand, if some system produces less waste than the others and this has not been taken into account, its environmental impacts are overestimated compared to the others (Finnveden 1999).

2.5.1.1 Multifunctionality and allocation

The first and most fundamental question to be asked when starting an LCA is: *what is the studied product system*. In case of waste management, the product can be identified differently depending on the perspective. From one point of view, the studied product is the infrastructure, in this case the waste incineration plant. From another perspective, the studied product is treatment of waste, or as most waste management systems produce also energy, the produced utilizable energy. Although all perspectives revolve around the same system, they all result in totally different results and possibly even conclusions.

What is however common for all perspectives is that waste management and especially waste incineration systems are often multifunctional systems. Waste incineration not only disposes waste, but also produces valuable products, independent of the perspective. Valuable products can then replace the use of primary materials for the production of similar goods. The way multifunctionality issues are treated is a methodological choice that has the greatest impact when numerous different systems are to be compared.

The multifunctionality issues can be solved by two approaches: by allocating the environmental impacts to the products or by expanding the system boundaries to include several products into the system. The latter approach is the one that is to be favored according to the international standards (ISO 14044). The first approach does not only conflict several principles of the LCA framework, but can also lead to biased results. (Finnveden 1999; Weidema 2001)

Ideally, system expansion makes it possible to avoid allocating the environmental impacts to the outputs of the system (Finnveden 1999; Weidema 2001). One way of performing a system expansion is to add the production of given good so that the two systems are producing equal amounts of valuable products as illustrated in figure 2.5 (Finnveden 1999). This method is however applicable only for comparisons of two or more product systems. If only one product system is studied, the system expansion does not provide one with a solution for dealing with multifunctionality issues, as it only ensures that the systems deliver the same function.

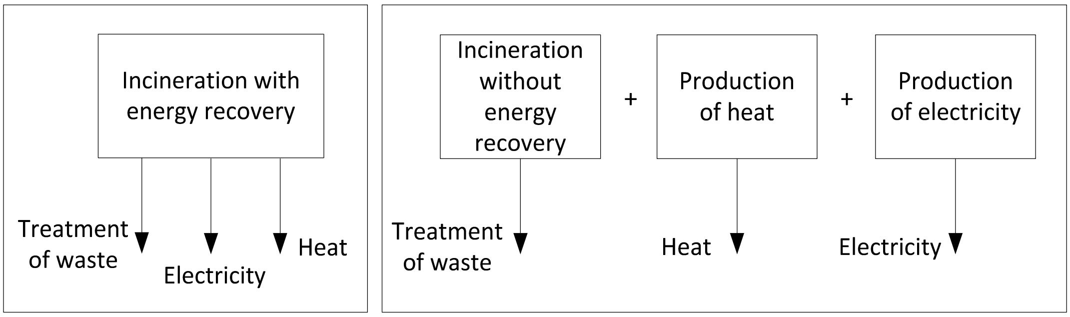

Figure 2.5. *System expansion targeted to avoid allocation by adding the production of good(s) to create processes groups with similar functions (Finnveden 1999)*

Another other way of carrying out system expansion is to subtract the environmental impacts of the production of similar good from the systems so that the overall system delivers only one good (Finnveden 1999; Weidema 2001). This approach simplifies the studied system into a single function system and is therefore applicable both for the comparison of numerous systems and for the study of a single one system. The second approach is presented in figure 2.6.

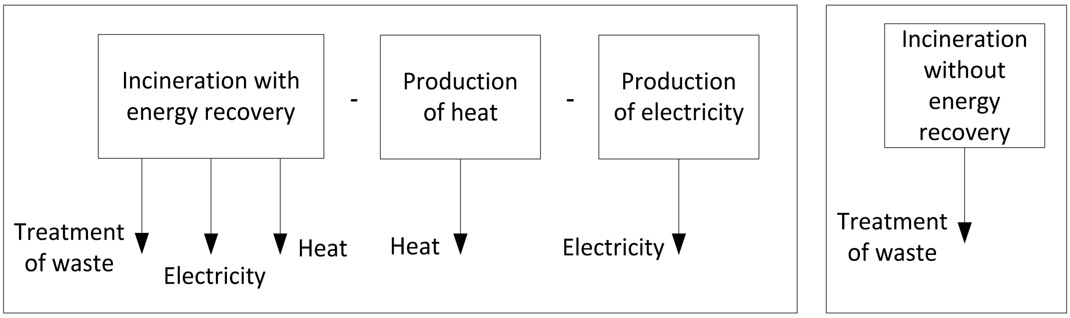

Figure 2.6. *System expansion targeted to avoid allocation by subtracting the production of good(s) to create processes groups with similar functions (Finnveden 1999)*

Even the second approach does however eliminate the problem by creating another. To carry out the system expansion, one has to decide which is the primary good delivered by the system and which are the secondary goods that replace other systems in producing them. It seems to be the general approach in LCAs of waste management system that primary good is the treatment of waste as indicated by the choice over functional unit. Even then, the necessary decision over alternative energy sources that are replaced by waste incineration can be decisive regarding the outcomes of the study (Finnveden 1999). A common assumption is that incineration replaces other types of fuels equally, i.e. the avoided burden is calculated based on average grid mix (Finnveden 1999). This is however an inaccurate assumption, since all parts of the background system are not affected equally by changes in waste management systems (Ekvall et al. 2007). For instance, it is very unlikely that the increased use of recycled fuels would decrease the use of hydro or nuclear energy as much as it would decrease the use of hard coal. The marginal changes in background systems should therefore be modeled using marginal instead of average data (Ekvall et al 2007).

In the case of Lahti Energia the new gasification plant is expected to replace the use of hard coal in energy production. On a less local scale the marginal technology might however differ from the reference case. In general, the fuel that is replaced by the increased use of other fuels can be determined by at least three different approaches:

- **The replaced fuel is the preferred fuel**, i.e. the fuel that would otherwise be used. In Europe the preferred fuel would be hard coal except for Northern Europe, where the preferred technology would be natural gas due to its lower emissions. Political decisions may however affect the choice over preferred fuel, and in some cases nuclear power might also be considered the energy source that is replaced. (Finnveden et al. 2005; Weidema et al. 1999)

- **The replaced fuel is the least sustainable fuel**, i.e. the fuel the use of which is intended to be decreased the most due to environmental objectives and motivators. Again, in Europe the environmentally least preferable fuel would be hard coal. (Finnveden et al. 2005)
- **The replaced fuel is a similar fuel**, i.e. the choice over fuel is decided based on availability of fuel and its applicability to the existing technology (Ekvall & Finnveden 2000)

The first approach is based on the assumption that the energy demand is rising and that the choice over energy source and energy production technology is for most affected by the increased demand and economical preference of different fuels (Finnveden et al. 2005). This assumption does however contradict a number of political decisions and objectives. In fact, Europe's energy roadmap 2050 lists both energy savings and increased use of renewable energy carriers as most important energy goals of the European Community (European Commission 2011a). The use of fossil fuels, and especially hard coal, is expected to be decreased the most in most of the presented scenarios indicating that hard coal is the most likely fuel to be replaced (European Commission 2011b). This suggests that the replaced fuel should be determined following the second approach, i.e. it is most likely the least sustainable fuel. This is in line with the prognoses for European energy supply, according to which the use of hard coal will be strongly cut while the energy use of biomass and waste is expected to increase (European Commission 2011a; European Commission 2011b).

According to the third approach the incineration of waste replaces primarily similar fuels, i.e. most commonly other fractions of waste. This approach is based on the underlying assumption that the incineration capacity is significantly smaller than the amount of burnable waste, and therefore if the studied waste fraction was not incinerated, other waste that is currently disposed in landfills would be incinerated instead. In a longer run the incineration capacity is however expected to increase until all combustible waste is being utilized. In situation like this, the replaced fuel would again be some fossil fuel, and since it is likely that the energy production in Northern Europe and in the rest of the Europe as well is heavily influenced by environmental motivators, the replaced fossil fuel would most likely be hard coal. In a sustainable scenario fossil fuels would on the other hand be replaced by renewable fuels and the competing energy source could therefore be for example biomass. Given the current policy definitions in Europe, which aim at increasing the share of renewable energy carriers at the cost of fossil ones and the prognosis for future European energy mixes, it is however unlikely that this kind of situation would emerge during the life time of the studied plant (European Commission 2011b). (Ekvall & Finnveden 2000)

In the case of heat generation one has to consider also the regional boundary settings independent of what approach is used for determining the replaced fuel. Heat can be used only locally, so it is primarily replacing fuels that are in use in the studied area (Weidema 2001). In Finland hard coal is used primarily in coastal areas and in Lahti, and can also be the replaced fuel only in these areas. However, it can be concluded based on the above mentioned information that hard coal is the most likely energy carrier to be replaced – at least during the expected life time of the studied plant and in places where it is already used for energy generation. In other regions hard coal is likely to be replaced as a source of electricity, while some local fuels are being replaced in the generation of heat.

Another problem associated with allocation arises with multi-input processes. The environmental impacts of waste treatment depend for one on the properties of waste (e.g. Sundqvist 1999, pp. 12). The environmental impacts of waste treatment systems are often measured based on mixed waste inputs and their comparison is therefore not feasible unless the environmental impacts are allocated to the different inputs (Gheewala 2009). Multi-input allocation has to be therefore carried out when comparing different product systems. When only one system is studied, no allocation is needed, but the input flow should still be qualitatively and quantitatively described to enable efficient analysis of the results.

2.5.2 Time aspects and resulting challenges in impact assessment

The emissions from waste management can in some cases take place over a long period of time, in some cases thousands of years. In life cycle assessments the emissions are however assumed to take place simultaneously and the emissions have to be therefore integrated over a certain period of time. (e.g. Finnveden 1999; Pennington et al. 2004)

The decision over the studied time frame can be decisive regarding the environmental impacts of the studied waste management systems: when incinerating waste, the emissions are released simultaneously where as in landfill the release happens over thousands of years (Finnveden 1999). The question on whether or not to include environmental impacts taking place in the distant future has not been unambiguously answered (Finnveden 1999; Gheewala 2009). It has however been argued that impacts on human health should cover both impacts on present and future generations (Jolliet et al. 2004). LCAs should also according to ISO standards cover all potential impacts (ISO 14040).

The exclusion of future environmental impacts is a clear value choice. Excluding impacts after a given period of time in fact indicates that the future generations are not considered important (Finnveden 1999). Also any discounting which places less importance on future emissions indicates that the well being of future generations is not considered as important as that of present generations.

SETAC-Europe working group on life cycle assessment has suggested that the environmental impacts should be analyzed over two different timeframes: an infinite timeframe to determine the maximum amount of emissions and a short time frame of 100 years (Udo de Haes et al.1999a; Udo de Haes et al.1999b). The benefit of such approach is that it improves the transparency of the results by dividing the environmental impacts to those taking place in near future and those taking place over the coming thousands of years (Ekvall et al. 2007). This approach has been used in life cycle assessments of waste management (Finnveden 1999) but still no consensus exists on where to draw the line with future impacts (Finnveden 1999; Gheewala 2009).

Another issue that has to be paid attention to when studying the long-term environmental impacts is the transparency and comprehensibility of the results. According to Ekvall and colleagues (2007), the target groups of an LCA study tend to focus on the results and disregard uncertainties and possibly also the resulting limitations in the study. A similar behavior has also been brought out by Bras-Klapwijk (1998). Ekvall and colleagues (2007) therefore suggest that parts of the study, where there is a high risk for uncertainty, might be best left outside of the study. Long-term emissions from landfills are clearly such situation, since the emissions and resulting environmental impacts are predicted based on limited initial data.

2.5.3 Spatial information

As discussed earlier, the environmental impacts taking place at different times are commonly summed up in LCA studies. This is the case also for emissions taking place at different locations (Ekvall et al. 2007; Pennington et al. 2004). In reality however, the emissions are likely to take place in numerous different locations (Rebitzer et al. 2004). The environmental impacts caused by the same amount of certain pollutant may be very different in areas with different environmental conditions (Ekvall et al. 2007). Also the release of emissions may depend on site-specific environmental conditions (Hellweg 2000).

The common negligence of spatial differences is in many cases the result of incomplete initial data. The LCA practitioner is in most cases not aware of the locations or the points in time (Pennington et al. 2004). As a result, the spatial variations may make it futile to incorporate site-dependent impact assessment methods (Pennington et al. 2004). This also makes it difficult to accurately estimate the impacts of occupational safety (Jørgensen et al. 2008).

The loss of spatial information limits the use of LCA. If site specific environmental conditions and impacts have not been taken into account, the LCA framework cannot be used to determine the optimal location of a waste management facility (Ekvall et al. 2007). This may also lead to uncertainty in the inventory data, as the differences in the release of pollutants has not been paid attention to.

2.5.4 Non-linear relationships

LCA models are in most cases based on linear or steady state models. In the case of waste management, this would for example mean that the environmental impacts of collecting and transporting waste would develop linearly, as illustrated in figure 2.7. This is however hardly the case: collecting waste requires establishment of infrastructure, and with high recycling rates the transportation distances and processing efforts may increase nearly exponentially, as illustrated in figure 2.7 as well. (Ekvall et al. 2007)

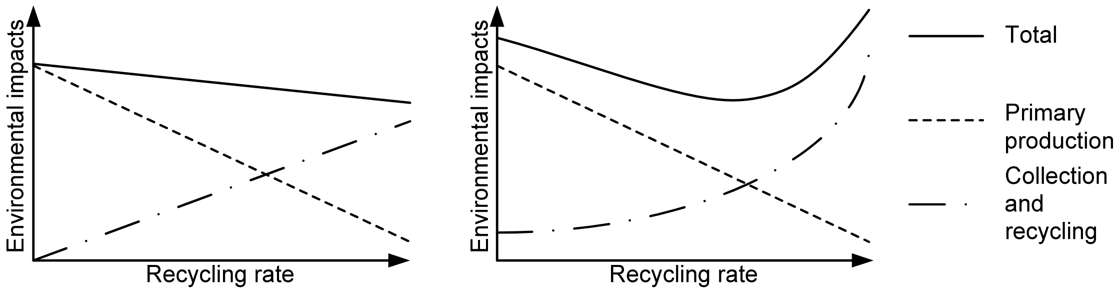

Figure 2.7. *On the left a linear model used in most LCAs to model the dependency of environmental impacts on a known variable and on the right a more realistic, non-linear model of the actual environmental impacts (Ekvall et al. 2007)*

The exclusion of non-linear relationships can be a major factor considering the occupational safety issues. As the increase in recycling rate for example is likely to result in drastically increased collection and recycling efforts, also the amount of occupational accidents along with other safety issues related to these efforts is likely to be drastically increased as well.

Similar non-linear behavior can be the case also for some environmental impacts (Udo de Haes et al. 1999a). Some methods have been developed that take into account the non-linear relationships of dose and response as well as that of fate and exposure behavior. However, both of the most widely used impact assessment methods, namely Eco-indicator 99 and CML-IA, omit all non-linear relationships (Cooper & Fava 2006; Guinée et al. 2001; Goedkoop & Spriensma 2001).

Non-linear behavior of dose-response and fate-exposure relationships could be considered by using impact assessment methods that do not omit non-linearities. This can however easily lead to more complicated data collection[2], and is therefore usually not done. The non-linearities in the relationships between required efforts and the amount of

[2] Considering non-linearities would require that in the case of waste incineration for example the height of stack, population density and background concentrations of emissions were known. This would then lead to the need for more specific time-related and spatial information, which is in most cases not available as discussed in chapter 2.5.3.

produced goods or services can on the other hand be considered by using non-linear mathematical models or linear-programming models when modeling the product system (Ekvall et al. 2007). This has been done for example by Metso in the life cycle assessment of LT106 rock crusher, which took into account the non-linear relationship between engine's operating speed and engine emissions (Kallio et al. 2011).

2.5.5 Interpretation of field data and information on specific pollutants

As discussed earlier, one of the major challenges associated with life cycle assessments of waste incineration is the fact that waste incinerators are often treating various different waste fractions simultaneously. This complicates also the interpretation of measured emission data: emission measurements are often based on mixed waste inputs making it difficult to allocate the emissions to different waste fractions. Furthermore, waste treatment facilities are often measuring the emissions, but not the composition of waste which makes the allocation practically impossible. (Sundqvist 1999, pp. 13-14)

A similar problem is associated also with emissions from landfills. The LCA models cannot be based on measured data since the emissions from landfills take place over a long period of time and since the release rate of emissions is likely to be non-linear in the long-run. Calculated data is therefore needed to complete measured data. (Sundqvist 1999, pp. 13)

The interpretation of field data is often complicated also because the emissions are measured using sum parameters such as total organic carbon (TOC). The environmental impacts on the other hand vary significantly between different substances covered by a single sum parameter. As a result, the LCA's ability to model actual environmental impacts is reduced. The problem could be avoided by avoiding the use of sum parameters, but given the enormous amount of different chemical compound and the fact that current legislation requires in some cases that measurements are done using sum parameters, complete avoidance of sum parameters is very unlikely (Ekvall et al. 2007; DIR 2000/76/EC). (Ekvall et al. 2007)

2.5.6 Treatment of biogenic greenhouse gas emissions

The treatment of biogenic greenhouse gas (GHG) emissions in LCA is a much debated issue. The absolute magnitude of GHG emissions depends on the chemical composition of waste, which varies between different waste incineration plants. However, when considering the environmental impacts the decisive factor is not the carbon content of waste or even the absolute GHG emissions, but rather the share of biogenic waste: the emissions resulting from the incineration of biogenic material are generally not considered within LCA studies or CO_2 accounting in general (e.g. Pipatti et al. 2006, pp. 6; European Commission 2010e; Johnson 2008; Johnke 1999). It has however been argued that one should take into account the emissions resulting from possible decrease in carbon stocks even if the GHG emissions released in the combustion have not been considered (e.g. European Commission 2010e; Johnson 2008).

Also differing opinions have been presented. Rabl and colleagues (2007) for example argue that biogenic GHG emissions should be considered similarly to fossil emissions. The difference between biogenic and fossil emissions would then result from possible removal of CO_2 during the growth of biogenic material. This along with the “polluter pays” principle presented by Rabl and colleagues (2007) would however lead to a situation, where the emissions from incineration of biogenic waste were considered as such whereas the credit for CO_2 uptake was allocated to the product itself instead of its disposal. The inclusion of also biogenic CO_2 has however not been widely promoted. On the contrary, according to the methodology suggested by European Commission (2010e) for the GHG emission calculations of biomass, neither the GHG emissions resulting from the incineration of biogenic waste nor the emissions caused before their collection should be considered. It is on the other hand suggested in the ILCD handbooks that all waste flows should be completely modeled until the final inventory results consist of elementary flows (European Commission 2010a, pp. 96). This is however typically not done when studying waste management systems (Finnveden 1999). Instead, life cycle assessments of waste management typically consider waste as a kind of elementary flow (Finnveden 1999).

All in all, the question on how to consider biogenic GHG emissions in the impact assessment is a complicated issue that has not been fully solved by this day. A very common approach at the moment is to differentiate biogenic and fossil emissions and to include only the latter when calculating global warming potential but still also other approaches are being used by for example ecoinvent (European Commission 2010a; European Commission 2010e; Hischier et al. 2010; Pipatti et al. 2006).

2.5.7 Other problems associated with LCAs of waste management

One major issue related to the use of LCA in supporting decision making over different waste management approaches is the fact that LCA does not answer all relevant questions. LCA does not for example contemplate all major environmental issues of waste incineration as listed by the European Commission (2006, pp. 9). Furthermore, LCAs do not typically consider all relevant sustainability issues but are mainly limited to environmental issues only (e.g. ISO 14040; Klöpffer 2008).

LCA has also been criticized since it does not follow the precautionary principle, i.e. uncertain environmental impacts are not paid enough attention to (Bras-Klapwijk 1998). This can be considered a major problem with the LCAs of waste incineration systems, since they treat thousands of different chemical substances. All the environmental impacts of some substances are not necessarily known, and LCA can therefore provide one with misleading results (Bras-Klapwijk 1998). The omission of precautionary principle can be demonstrated with the common use of sum parameters: the group of polycyclic aromatic hydrocarbons (PAH) contains tens of substances, of which at least 13 are known to be carcinogenic (Hallikainen et al. 2010, pp. 89). The Eco-indicator 99 methodology, which is the most widely used impact assessment method, does not however contain characterization factors for carcinogenic human health impacts for all of the substances (Cooper & Fava 2006; Goedkoop & Spriensma 2001). Furthermore, the characterization factor for the sum parameter is significantly lower than that for the most harmful substance in the group (Goedkoop & Spriensma 2001). This is a clear violation of the precautionary principle, and can in extreme cases lead to significant underestimation of the actual environmental impacts.

LCA methodology has on the other hand been criticized, because it risks also the opposite. The combination of conservative estimations, integration of impacts over time and space and assumption of linear dose-response relationship can lead to worst-case or even impossible scenarios (Owens 1997). In the case of waste incineration this can prove to be a major drawback of the tool, since the industry is already faced with prejudices and resistance. Any clear overestimation of the impacts can therefore lead to unnecessary and unwanted misinterpretations.

3 Materials and methods

The primary goal of this study is to evaluate the applicability and feasibility of including occupational safety into the LCA framework from Metso's point of view. Secondarily, this study will also support any future life cycle assessments carried out in Metso Power regarding the use of recycled fuels for energy generation.

In order to answer all research questions, a two step approach is needed. The applied part of this study therefore consists of two parts: a theoretical part aiming at determining the technical possibility and feasibility of studying occupational safety within the LCA framework, and a practical part aiming at determining whether or not such study is feasible from practical point of view.

3.1 Development of suitable methodology for Metso Power

3.1.1 Goals of the methodology development

The first part of this thesis, titled *Inclusion of occupational safety in LCA*, is built around a literature review, the purpose of which is to collect information about the existing motivators and methods for including occupational safety in LCA. Based on this, the existing methods and also barriers hindering such inclusion will be evaluated to determine the technical possibility of including occupational safety in LCA.

The different methods for including occupational safety will also be evaluated to determine the best suitable method for the needs of Metso Power. The evaluation will consider not only if the methods are suited for meeting the needs, but also if they are in line with existing standards and good practice guides. Based on this evaluation, one method will be selected, or if necessary developed, to be used in the case study.

The selection of the proposed method is based on a number of criteria. The criteria are established following the needs of Metso Power. The main focus is however to evaluate the need for having such a methodology in place, and no perfect coverage of all criteria is therefore considered essential.

3.1.2 Data sources for the evaluation and identification of methodologies

Material for the literature review will be collected from standards (ISO 14040, ISO 14044), guidebooks (above all ILCD handbooks) and scientific articles published in for example

International Journal on Life Cycle Assessment. Metso Powers needs will be determined through personal communications with Metso Powers HSE department.

For the methodology development, three types of publications have been reviewed:

- Publications aiming at evaluating future development needs of LCA towards covering also occupational safety issues
- Publications studying and evaluating the need for different modifications of “traditional” LCA framework to more extensively cover all potential impacts
- Case studies and background reports covering also impacts on human health

The publications are searched for using different search engines, including *Google Scholar*, TUT’s *Nelli* search engine, and the online search engines of a number of scientific publishers including for example *Springer*, *Elsevier* and *American Chemical Society*. Also material from unpublished sources of literature (for example presentations at LCA related conferences) will be used in case available.

3.2 Case study

3.2.1 Goals of the case study

The second part of this thesis, titled *Case study of a waste gasification plant*, is based on a case study of one of Metso Power’s products. The purpose of the case study is to determine if the inclusion of occupational safety is practically possible, and if it adds any value to LCA studies or the study of occupational safety.

The practical possibility will be determined through data availability, laboriousness of the study and validity of the results. The feasibility of the study will be evaluated based on the information provided by the study: does it provide any new information, does it prove that inclusion of occupational safety in LCA is relevant from LCA point of view, and are the results relevant for decision making within Metso Power or its stakeholders. Considering the relevance, this study should determine if there is a risk of trade-offs between environmental impacts and occupational health, if their inclusion provides some added value to LCA studies, and if the motivators of Metso Power can be reached in practice.

3.2.2 Scope of the study

3.2.2.1 Type of LCA method applied

In order to simplify the case study, it will be carried out as a screening LCA. Whether or not the LCA framework to be followed is fundamentally based on SLCA or LCA will be determined as a part of the methodology development in the first part of this thesis.

The study is in general carried out and reported according to the applicable requirements of ISO 14040-14044 independent of the methodology to be followed. GaBi 5 software will be used for the modeling of the product system and the impact assessment.

3.2.2.2 Studied product system

The product system to be studied in the case study section of this thesis is a waste gasification plant delivered by Metso Power to Lahti Energia in Finland. The gasification plant is first of its kind and presumably the first gasification power plant in the world to efficiently generate electricity and district heat from recycled fuels. During the operation of the plant recycled fuels are gasified and the product gas is incinerated to produce electricity and heat. In addition to the operation of the plant itself, the case study will consider also the manufacturing and disposal of the plant as well as all relevant upstream and downstream processes.

The plant has a fuel power of 160 MW and will produce 50 MW of electricity, and 90 MW of district heat. The plant uses recycled fuels (REF) for the generation of energy. The fuel is processed at a preparation facility prior to its combustion.

3.2.2.3 Functional unit and system boundaries

The studied product system is a multi-functional product, which produces both electricity and heat besides the disposal of waste. In this study two alternative ways of dealing with the multi-functionality will be applied:

1. The environmental impacts are allocated completely to the gasified REF
2. The heat and electricity produced while disposing waste are considered avoided burdens

In the second case the alternative energy source is taken as hard coal as suggested in chapter 2.5.1. Functional unit of this study is determined as the gasification of one ton class I-II REF in a REF gasification plant in both cases. Gasified REF serves as the reference flow of this case study.

System expansion is taken as the primary way of coping with multifunctionality issues of also other processes than the waste disposal process itself. Allocation has however been resorted to in case system expansions lead to the product system becoming overly complex. In such cases the allocation principles have been determined specifically for the respective process based on recommendations given in literature.

The study is intended to describe a steady state situation and no major changes in the background systems are assumed to occur due to the operation of the plant. Therefore no non-linear relationships have been considered. As a result, it should be noted that this study is not suited to support decision making that would require the study of non-linear relationships (e.g. decisions regarding the optimal locations of waste management systems).

As the purpose of this study is not to compare the emissions resulting from different waste incineration plants or from the incineration of specific type of waste, the emissions of the plant do not need to be allocated to the different inputs. Due to this, the outcomes of this study are applicable only for plants that are using class I-II REF as a fuel and cannot be generalized to other waste incineration plants.

3.2.3 Inventory assessment methods and data quality requirements

The case study will be carried out as a screening LCA meaning that no detailed information is intended to be collected for all parts of the product system. The analysis will however be done as a part of a more detailed life cycle assessment of the same product making it that a lot of case specific inventory data is available[3]. The same models of the product system will be used as in the case of the detailed LCA study.

In this case study all of the information that is intended to be used in the latter study will not however be used. Instead, the analysis will be carried out using data from literature and calculated data from Metso's internal data sources. The study is done mainly based on literature data to ensure the confidentiality of more detailed data. Data from Metso's internal sources will be primarily calculated data. Literature sources used consist of various LCI databases (mainly GaBi and ecoinvent databases), national and European Statistics and other published sources of literature. The LCI databases are in most cases subject to charge and can be accessed only by registered users. The background documentation on the other hand is available free of charge for all databases used for this study[4]. Certain parts of the product life cycle are left beyond the scope of the study in case they can safely be assumed to be insignificant regarding the overall outcome. The study of environmental impacts should however cover the same aspects as the study of occupational safety as argued by e.g. Klöpffer (2008).

In order not to compromise the reliability of the results, case specific data has to be collected at least for the most important processes. To identify these processes, the studied system is divided into foreground and background processes. The latter will be studied solely based on data from literature, while the foreground processes will be studied using case specific data whenever available. The division between foreground and background processes is done following the specificity perspective, as illustrated in figure 3.1. In figure 3.1, processes marked with bold font are treated as foreground processes, and processes marked with normal font are treated as background processes. Some processes are identified as foreground processes, but no case specific data is available for all parts of them due to a number of reasons. These processes are marked with bold italic font.

[3] The results of the detailed LCA will focus on the environmental impacts of the plant and will not be disclosed to public at this point. The detailed LCA is not a part of this thesis.
[4] Documentation of GaBi database can be found at http://database-documentation.gabi-software.com/support/gabi/ and the documentation of ecoinvent database at www.ecoinvent.ch

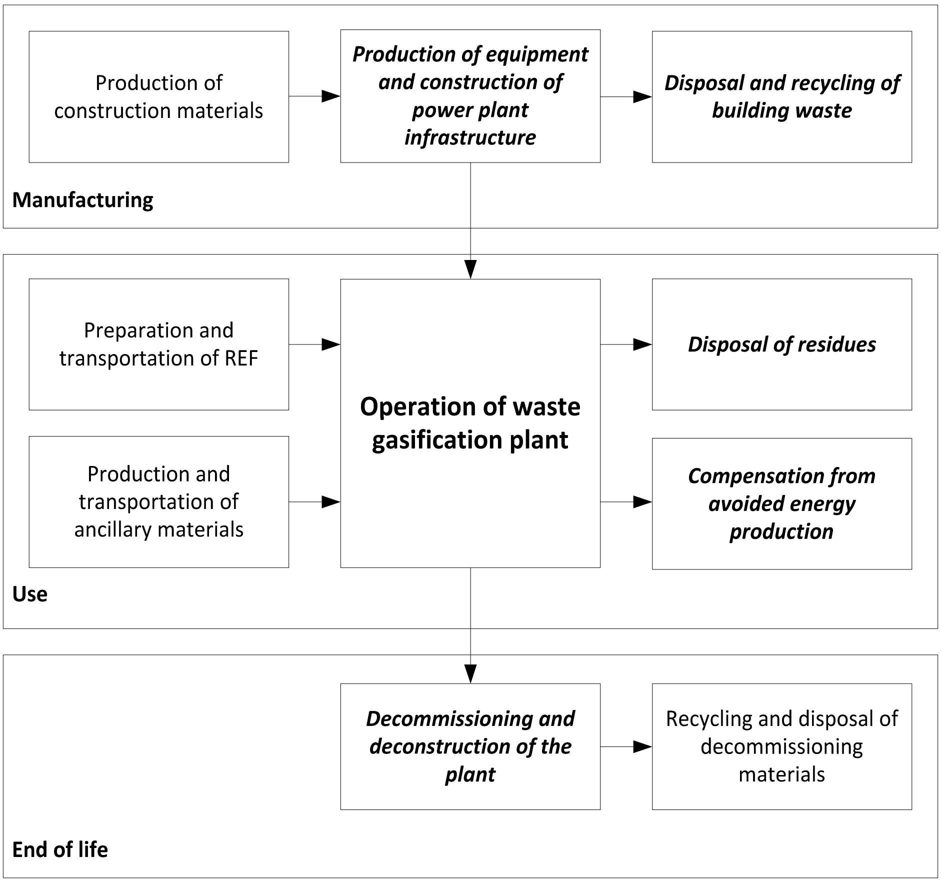

Figure 3.1. *Division of the product system in foreground (bold font), foreground with limited data availability (bold italic font) and background processes (normal font)*

No cut-off criteria will be considered for this study as the determination of the theoretical 100% coverage would make the study considerably complex.[5] Instead, this study will consider all background processes included in the system, and all elementary flows originating from foreground processes regarding which information is available.

No strict data quality requirements are set for this study either. Given that the purpose of this study is to define the possibilities for including occupational safety in LCA framework, the definition of attainable data quality is a part of this study. Therefore, the data quality is in fact one outcome of this study instead of a perquisite for it. Some general guidelines can still be defined to guide the data collection. As a rule, the data should be up

[5] In practice defining the 100% coverage requires the modeling of the entire product system using some data estimates for the parts only limited or no information at all is available. When the study focuses on environmental impacts only, this can be done using data given in a variety of databases. For occupational safety such databases do not exist, and the definition of complete coverage would therefore require extensive collection of data regarding the types of processes affected and their occupational safety issues.

to date, represent the studied geographical region and technology, and be collected over a sufficiently long period of time to eliminate random variations.

A major difficulty with collecting input and output data is that emissions from waste incineration plants are often reported using sum-parameters. The breakdown of emissions to individual compounds has not been considered necessary for this study given that the study primarily aims at testing the proposed method for including occupational safety in LCA. Sum-parameters have therefore been considered as such.

3.2.4 Impact assessment methods

As the purpose of this study is to determine the possibilities and feasibility of including occupational safety within the LCA framework, **only impacts on human health will be considered**. Impacts on other areas of protection will be excluded from this study making it that the study does not reflect all relevant environmental impacts.

Environmental impacts on human health will be assessed using Eco-indicator 99 as impact assessment method and DALY as category indicator. Occupational safety on the other hand will be assessed through the method discussed in chapter 4.4 using DALY as indicator. Also midpoint impacts will be evaluated for the part of occupational safety using the amounts of fatal and non-fatal accidents as category indicators.

A large share of the environmental impacts can be expected to take place in relatively distant future. These environmental impacts are also worth considering. Following the recommendations given in literature (see chapter 2.5.2), the **time frame will be divided into two parts: a short period timeframe considering the first 100 years, and an infinite time frame**.

The **spatial differences have not been taken into account** in this study as there are no impact assessment methods available that could be used to consider local conditions in the studied geographical area. As a result, this study must not be used to justify any decisions made regarding the optimal locations of waste management systems.

The **biogenic greenhouse gas emissions have not been considered when determining the emissions contributing to global warming**. The guidelines proposed by European Commission (2010e) have been used for determining the GHG emissions of the waste incineration. The emission factor for waste is taken as reported by Statistics Finland (2012a).

3.2.5 Interpretation and use of results

Results will be interpreted to find out the processes contributing most to the overall impacts on human health, environmental health and occupational health and safety. Also the sensitivity of results will be determined. However, as there is no uncertainty estimates available for most of the data, the sensitivity will be determined mainly through qualitative and semi-quantitative analyses.

The results of this case study are primarily intended to be used internally within Metso Power. The results will also be available to Metso's external stake holders. The **results are not intended to support any comparative assertions** by Metso or any third party. Furthermore, the **results of this case study do not provide one with information related to risks or actual environmental impacts** taking place in a given place at a given time.

4 Inclusion of occupational safety in LCA

This chapter provides one the results of the methodology development section. The section aims first of all to study the possibility and feasibility of including occupational safety into the LCA framework at a very general level. The second purpose is to determine the most appropriate method for including occupational safety into the LCA framework. Finally, necessary initial data that can be used in the case study as well as possible further studies will be given in this chapter.

This chapter will focus on the possibility to include occupational safety into LCA framework from a technical point of view only. The questions related to practical issues will be answered through the case study. Also the proposed method will be determined based on technical and methodological feasibility. The practical feasibility of using the method will again be examined through the case study.

General data provided in this chapter is intended to support the implementation of the proposed method. No directly applicable inventory or impact assessment data is intended to be given in this chapter. Instead the data should support the calculation of inventory data. Data given here will be collected primarily for the needs of the case study. In practice this means that the data will be collected for those processes that are relevant considering the case study, and that the data is in line with the boundary settings of the case study.

4.1 General motivators for and against

Human health impacts have been suggested to be studied as a part of life cycle assessment by numerous organizations developing the LCA framework. On general, the focus has been on identifying and assessing human health impacts resulting from the decrease in quality of the environment (environmental health). Issues related to occupational health and safety have also been suggested to be studied within the LCA framework, but they are commonly left outside of the recommended impact categories (Udo de Haes et al. 1999a; Guinée et al. 2001; European Commission 2010a, pp. 95; Jolliet et al. 2004). Furthermore, impacts on human health arising from occupational accidents or working environment conditions are not explicitly included in the recently promoted LCA framework (European Commission 2010a, pp. 95). It is even suggested that even if such impacts were considered within an LCA study, they should be interpreted and analyzed separate from the environmental impacts associated with everyday operation of the studied product system (European

Commission 2010a, pp. 95). Some studies have however shown that not studying occupational health and safety can lead to trade-offs between environmental impacts and occupational health and safety, which then gain conflicts the general idea of life cycle thinking (Hellweg et al. 2005; Reap et al. 2008; Pettersen & Hertwich 2008; Hofstetter & Norris 2003; Kim & Hur 2009). As a result of dissenting recommendations, there is a strong disintegration in the opinions of LCA practitioners when it comes to the feasibility of including occupational health impacts into the LCA framework (Pettersen & Hertwich 2008; Hofstetter & Norris 2003).

A number of arguments can be found supporting the exclusion of occupational accidents from LCA framework (e.g. Pettersen & Hertwich 2008; Hofstetter & Norris 2003). A major reason for not considering occupational accidents is the fact that occupational accidents are a result of abnormal function of the system. LCAs only rarely consider emissions and impacts associated with abnormal situations or operation of the product system (European Commission 2010a, pp. 95; Frischknecht et al. 2007). It has been argued that linear behavior – which is commonly the basis of LCA – cannot be assumed for accidents occurring relatively rarely and that their inclusion in the LCA framework is not feasible (Jolliet et a. 2004). It has also been argued that the accidents could be prevented if the system functioned as it should and that the occupational accidents are not therefore related to the system itself, but rather its poor operation (Pettersen & Hertwich 2008).

The exclusion of impacts resulting from abnormal operation of products has on the other hand been questioned since it risks drawing false conclusions. The power of LCA studies is their ability to provide objective and transparent results considering all relevant aspects of the product system. It should in all cases be made clear if some relevant aspects are not paid attention to, and these aspects should then be studied separately. However, LCA results are commonly misinterpreted by neglecting any supporting qualitative data and data answering questions not included in the scope of an LCA study. Such risk is associated with the exclusion of impacts arising from abnormal situations: abnormal situations are on numerous occasions suggested to be studied through separate analyses, for example risk assessments. History has shown that complementary assessments and studies are easily dismissed and the attention focused on a single assessment – even if it does not answer all relevant questions. In addition, analyzing occupational health issues in retrospect adds complexity to the management system and increases in many cases the financial costs (De Benedetto & Klemeš 2008). (Bras-Klapwijk 1998; Jolliet et al. 2004; Jönsson 2000)

Another argument used to support the exclusion of occupational accidents and their impacts on human health is that workforce is not a part of the (external) environment and should not therefore be studied within the LCA framework, which according to the standard focuses on environmental impacts only (Pettersen & Hertwich 2008; ISO 14040; Hofstetter & Norris 2003). Both arguments supporting the consideration of workforce as a part of the environment and those opposing it have been presented with valid rationalization (Pettersen

& Hertwich 2008). On the other, the inclusion of occupational safety into the LCA framework has been promoted from two separate points of view:

1. Impacts arising from occupational accidents have been suggested to be studied as an impact on human health as a part of environmental impacts (e.g. Pettersen & Hertwich 2008).
2. Social issues in broader perspective have been suggested to be studied through social life cycle assessments (e.g. United Nations Environment Programme 2009), which is basically an extension of the traditional LCA framework with some necessary modifications (United Nations Environment Programme 2009; Benoît et al. 2010).

The question whether workforce is or is not a part of the environment is therefore more academic than practical. Even if workforce was considered not to be a part of the environment, its inclusion in the LCA framework could easily be justified by expanding the definition of the analysis from environmental to socio-environmental life cycle assessment. In addition, the division between external and internal environment is an artificial definition, which is not required by the LCA standards but rather comes down to the goal and scope definition of the study and motivators affecting it (ISO 14040; ISO 14044; Hofstetter & Norris 2003; Kim & Hur 2009).

The exclusion of occupational health impacts has also been justified, because the collection of data related to them would complicate the assessment (Hofstetter & Norris 2003). It has also been argued that LCA practitioners in general lack the required knowledge in occupational health (Hofstetter & Norris 2003). The LCA framework is indeed a compromise between the accuracy of the tool and its simplicity, and including any new aspects into the framework can easily lead to it becoming more complex (Klöpffer 2008). Methods have on the other hand been developed, which aim at simplifying the data collection procedure and some commercially available LCA databases even include information on occupational accidents. In addition, the responsibilities for environmental and occupational health and safety in companies are often within the same group or person (Hofstetter & Norris 2003). According to Cooper and Fava (2006) in 12% of all cases the LCA is supported or managed by the organization’s HSE function, as is the case also in Metso Power.

On the other hand, a number of arguments have been made in favor of studying occupational accidents within the LCA framework. Perhaps the most commonly issued argument is the fact that studying occupational accidents within the LCA framework helps minimize the risk of trade-offs (e.g. Pettersen & Hertwich 2008; Hofstetter & Norris 2003). The common exclusion of occupational accidents – and issues related to work environment in general – can risk improving product’s environmental performance at the cost of work environment (Kim & Hur 2009; Hellweg et al. 2005; Hofstetter & Norris 2003; De Benedetto & Klemeš 2008). The identification of trade-offs has commonly been considered a major strength of the LCA framework. However, in case the study does not cover all impacts, all possible trade-offs cannot be identified and avoided. It has been argued that occupational health impacts should be incorporated into the LCA framework to enable the minimization of overall impacts from a broader perspective (Hofstetter & Norris 2003). This would also support the overall aim of an LCA study to identify and evaluate all *potential* environmental impacts of a product system as well as help develop the tool towards a more comprehensive life cycle sustainability assessment[6].

In fact, the environmentally preferable solution is not necessarily the best solution regarding occupational safety – let alone sustainability in a broader sense (Kim & Hur 2009; De Benedetto & Klemeš 2008). Case studies have shown that the occupational accidents can in some cases be the primary cause of impacts on human health and that excluding them from the assessment would lead to severely misled conclusions (Ancona et al. 2010).

The exclusion of (occupational) accidents can also risk the focus of debate heading the wrong direction (Cowell et al. 2002). Focusing only on assessing environmental impacts can lead to a situation, where the debate focuses around and decisions are made based on environmental preference only. This can lead to biased decision making that does not ensure the optimal solution for the overall system and all its impacts on the surrounding world. For this, e.g. De Benedetto and Klemeš (2009) suggest that LCA as a tool that supports decision making should cover also work environment.

The inclusion of occupational safety into the LCA framework has also been justified from risk management perspective, since it allows the gathering of data regarding outsourced operations. Hendrickson et al. (2006, pp. 149) state that even though companies have successfully improved workplace safety, they have failed to improve the overall safety related to the life cycle of their products. Main reason for this is said to be the fact that there is no information regarding the importance of supply chain for the overall safety of a product system. LCA framework is considered to be an effective means of improving the awareness and that way of improving the overall safety from a broader perspective. (Hendrickson et al. 2006, pp. 149-151)

It has also been argued that assessing and controlling both environmental and occupational health impacts motivates the employees to minimize the both (Hofstetter & Norris 2003). Traditionally, the approach has been to assess environmental impacts separate from occupational impacts (e.g. Honkasalo 2000). The core benefit of the traditional approach is that it enables more accurate analysis. On the other hand, as pointed out by Bras-Klapwijk (1998), decision makers or any other human being for that matter tends to settle for a single source of information supporting their views and turn down any contradictory information. Given the fact that environmental superiority can in many cases

[6] Life cycle sustainability assessment is a term used by e.g. Kloepffer (2008) to describe an assessment considering all three aspects of sustainability (environmental, social and economical).

contradict occupational safety, it can easily be concluded that providing all necessary information in a single format could improve the awareness and eventually also the motivation of employees towards minimizing both environmental and occupational health impacts.

Finally, it has been argued that assessing merely environmental impacts – let alone merely impacts on external environment – is not a sufficient metrics (e.g. Kim & Hur 2009; Kloepffer 2008). Carrying out a comprehensive assessment would therefore require that no impacts on human health – including occupational health – are excluded from the assessment (Finnveden et al. 2009).

To conclude based on the above mentioned arguments in favor and against, **the inclusion of occupational health into the LCA framework is fundamentally a matter of adjusting the scope to meet the goals of the study** (Hofstetter & Norris 2003). In fact, several impact categories can be excluded from the LCA framework, among others occupational health, as long as their study is not required to meet the goals set for the study. In order to achieve best possible coverage, LCA should cover all relevant impacts. If a more comprehensive sustainability assessment is required, the coverage should be even more extensive covering also social and economical impacts (Kloepffer 2008). The inclusion of occupational health can therefore be justified if there is a reason to suspect that it is a relevant issue regarding the studied impacts. This can however be decided only based on existing studies regarding similar product systems, which provide one with very dissenting information regarding the occupational health impacts of waste incineration (Ancona et al. 2010; Vandecasteele et al. 2007).

4.2 Motivators for Metso and Metso Power

Metso published its group-wide HSE policy in 2011. The policy is supported by Metso top management and is intended to support the development of a safe, healthy and well-managed work environment. To fulfill the HSE policy, Metso promises to *"design its solutions, products, innovations and services to help its customers improve their safety and environmental performance"* (Metso 2011). With this promise, Metso is committed to life cycle thinking. The implementation of life cycle thinking has been supported by a group-wide LCA pilot project, during which four life cycle assessments were carried out.

Metso's HSE policy is also an example of the relationship between environment, health and safety issues within the company. In Metso health, safety and environmental issues are managed under the umbrella of HSE. As environmental issues go hand in hand with health and safety, it is important to create solutions that improve all three aspects instead shifting burden from one to another. LCA supplemented with occupational safety is seen in Metso Power as a way to link the two issues and also to simplify the field without creating additional tools to be used next to the existing ones.

Another motivator is to gain better knowledge regarding the HSE issue over the entire life cycle of the product. As stated in Metso's HSE policy and also in Metso's mission, the company strives towards sustainability not only through its own operations, but also through its products. Traditionally, occupational safety has been monitored within the premises and operations of Metso Power: in the production sites, offices and construction sites. Safety issues related to the use of products are on the other hand less well known. They have not been systematically monitored, and scattered pieces of information have been received only through informal channels. The time after the product is released to the customer is none the less important to Metso Power, and it is important that the right people are made aware of the performance of the product – both in technical and in safety sense. Life cycle thinking and LCA can help in this by gathering information from processes that are indirectly linked to the use of the product and cannot be directly influenced by Metso Power. LCA can also be helpful by linking the safety related to the use of the product to the safety of its manufacturing.

LCA can also be helpful in the implementation of HSE aspects into product development by providing information about the HSE issues over the entire life cycle of the product. At the moment, HSE issues are not systematically monitored during product development. LCA can provide one with a tool for systematically following and forecasting the impacts – both direct and indirect – of decisions made during the product development process. LCA cannot provide the kind of detailed information that is needed when planning for example mechanical safety features, but can be used to identify processes with high occupational safety risks. These processes can then be avoided if possible, or at least paid very close attention to when designing the detailed construction or operation.

The fourth motivator for this study and the inclusion of occupational safety into the LCA framework is to create fact based material for marketing and sales. At the moment LCA based information is used in marketing to highlight the environmental benefits of Metso Power's products. Expanding the coverage of these studies to occupational safety issues as well could make it possible to visualize the benefits in that field as well.

4.3 Methods for assessing occupational safety in LCA

As discussed in previous chapter, the occupational safety can be seen as a part of LCA framework from two different perspectives: as a part of environmental impact assessment, or as a part of social life cycle assessment. The choice over perspective is foremost a methodological choice. It basically determines how occupational safety is measured and assessed within the LCA or SLCA framework.

4.3.1 Occupational safety within LCA framework

The (environmental) life cycle assessment is used to assess impacts of a product system on environment. The impacts can be measured anywhere along the environmental mechanism from the inventory results to category endpoints. Category endpoints can be further grouped into areas of protection. Human health is one of the three areas of protection included in the LCA framework[7]. Currently, LCA studies assess impacts on either category midpoints or endpoints, or both. Both approaches have their pros and cons: using category midpoints as a basis for the impact assessment results in more accurate estimates of environmental impacts. On the other hand, the results are more abstract and harder to assess. The category endpoints then again are easier to grasp and more simple to assess due to the smaller amount of different impact categories. However, the results are also more inaccurate due to the vast number of simplifications and assumptions required to determine the dose-response relationship. The division of human health impacts in different midpoint and endpoint impact categories is presented in figure 4.1. (ISO 14044; Antikainen et al. 2012, pp. ; Udo de Haes et al. 1999a; Udo de Haes et al. 1999b; European Commission 2010b; Baer et al. 2000)

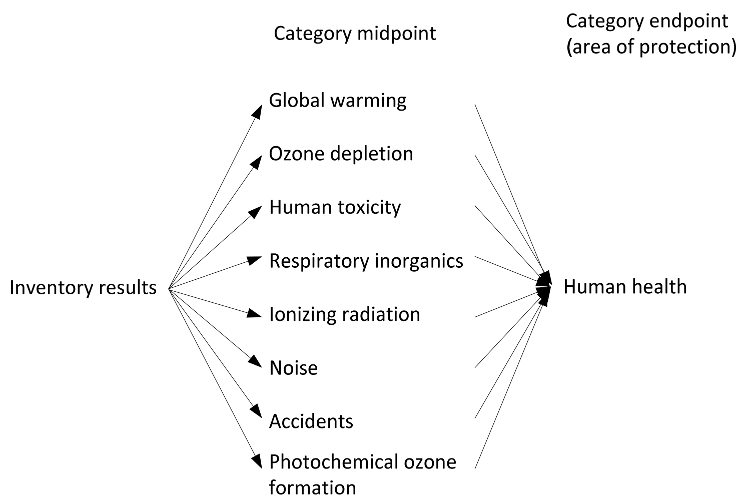

Figure 4.1. *Classification of environmental impact categories affecting human health according to ILCD handbook (European Commission 2010b, pp. 3)*

The impacts on human health arise through numerous cause-effect chains from direct health impacts due to e.g. exposure to radiation to indirect health impacts arising from

[7] The other two areas of protection are natural environment and natural resources. Also a fourth area of protection has been proposed, namely man-made environment, but it has been commonly left outside of the LCA studies. (Udo de Haes et al. 1999b; Jolliet et al. 2004)

decreased crop production or flooding due to e.g. global warming. The impacts on human health include not only fatalities, but also medical conditions (e.g. malnutrition), diseases and injuries. Simplified cause-effect chains are presented in figure 4.2.

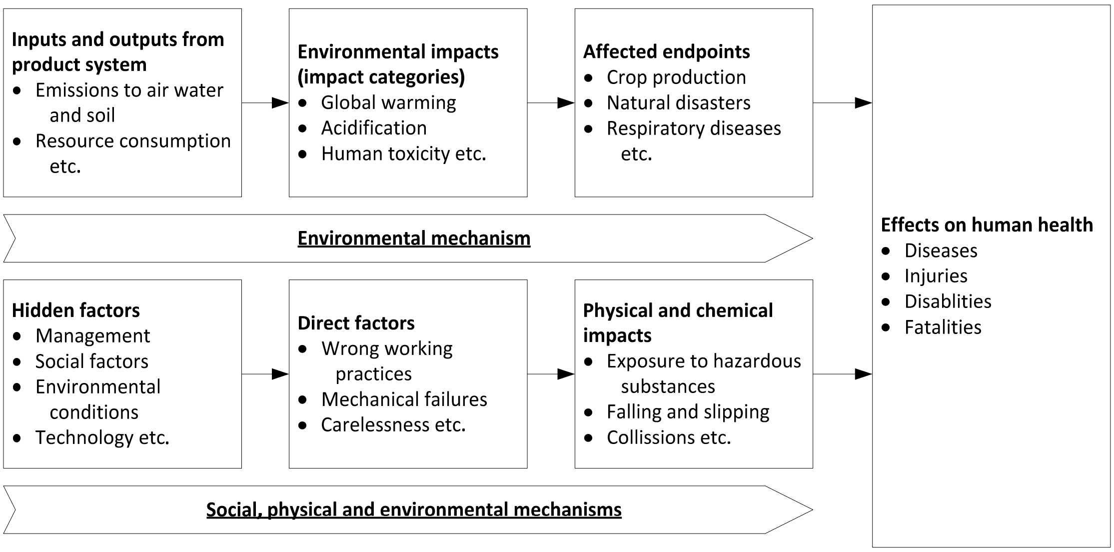

Figure 4.2. *Simplification of cause-effect chains leading to impacts on human health for both environmental and occupational health impacts*

Most of the human health impacts studied within LCA framework are indirect impacts. In LCA framework human health impacts are studied based on an approximation of exposure, dose and response, which can in some cases be overestimated (Owens 1997). The sensitivity of different regions to for example flooding is furthermore very different, and the actual impacts on human health may differ significantly depending on e.g. the location and point in time of the emission release (Owens 1997; Ekvall et al. 2007).

Occupational safety has been studied within LCA framework using both midpoint and endpoint indicators. Some studies and proposals for impact assessment methods have focused on assessing the work environment exposure to hazardous substances at midpoint level (e.g. Jönsson 2000), while some have concentrated on assessing the human health impacts resulting from occupational accidents at category endpoint (e.g. Hofstetter & Norris 2003). Also studies, where both occupational accidents and the exposure to hazardous substances are included, have been carried out using both midpoint and endpoint approaches (e.g. Kim & Hur 2009; Ancona et al. 2010; Schmidt et al. 2004).

Most of the recent studies have assessed occupational safety at category endpoint using disability adjusted life years as category indicator (e.g. Pettersen & Hertwich 2008; Ancona et al. 2010; Kim & Hur 2009; Hofstetter & Norris 2003). *DALY* is a unit established by World Health Organization (WHO) and takes into account both diseases and conditions leading to death, or temporal or permanent disability (World Health Organization 2012a).

$DALY$s can be calculated using equation (1), in which YLL denotes years of life lost due to ill death and YLD years of life lived with disability. YLL and YLD can be calculated using equations (2) and (3), where N is the number of deaths, L_f standard life expectancy at age of death, I number of incident cases, DW disability weight and L_d average duration of the case until remission or death (World Health Organization 2012a).

$$DALY = YLL + YLD \quad (1)$$

$$YLL = N * L_f \quad (2)$$

$$YLD = I * DW * L_d \quad (3)$$

The calculation of $DALY$s follows the basic method for impact assessment in LCA: the magnitude of elementary flow, in this case the amount of certain type of occupational accident, is multiplied by characterization factor (life expectancy for fatal accidents and disability weight multiplied by average duration of the medical condition for non-fatal accidents). $DALY$s can be calculated using social weighting, which strives to take into account the difference between impacts to people at different ages. World Health Organization uses 3% time discounting and age weights giving less weight to years lived at young and older ages. Most LCIA methodologies on the other hand do not apply any discounting or age weighting, although weighting is included in the LCA framework as an optional element. (World Health Organization 2012b, European Commission 2010c; ISO 14044)

One of the benefits that using indicators at category endpoints has, is that it enables the combination of occupational health impacts with environmental health impacts, which are also commonly measured using $DALY$ as metrics. This then again enables that trade-offs between environmental and occupational health impacts can be efficiently avoided. Some LCIA methods dealing with endpoints related to human health are summarized in table 4.1.

Whether or not environmental and human health impacts should actually be combined, is however an open question. According to Hofstetter and Norris (2003), people tend to value the risks related to environmental and occupational health impacts differently. The consequences of these impacts cannot none the less be justified in any case, and it is therefore feasible to avoid increasing the impacts in any case.

***Table 4.1**. LCIA methods considering effects on human health at category endpoints (European Commission 2010c; Goedkoop & Spriensma 2001)*

Method	Geographical coverage	Time horizon	Unit
Eco-indicator 99	Europe / world	Ca. 100 years	$DALY$s (age correction depending on cultural perspective)
IMPACT 2002+	Europe	Infinity	$DALY$s (without age correction or discounting)
LIME	Japan / world	Depending on impact category	$DALY$s
ReCiPe	Europe / world	20a, 100a or indefinite depending on cultural perspective	$DALY$s (without age correction or discounting)

4.3.2 Occupational safety within SLCA framework

Social life cycle assessment (SLCA) strives to expand the coverage of LCA to the social aspect of sustainability. SLCA is intended to cover e.g. human right, health and safety, governance and cultural heritage issues. The drawback of SLCA is that the method is fairly fresh and is not as well supported by software and database solutions as LCA. (United Nations Environment Programme 2009, pp. 9-10)

The SLCA follows the basic framework of LCA, but has also some differences compared to it. One is the use of qualitative indicators: within the LCA framework, environmental impacts are almost without exception assessed using quantitative indicators. SLCA on the other hand promotes the use of both qualitative and quantitative indicators. An example of the use of qualitative and semi-qualitative indicators is provided by Ciroth and Franze (2011), who studied both the social and environmental impacts of a laptop computer. The social impacts, including occupational health and safety issues, were studied through a more qualitative performance assessment and combined with environmental impacts only through a qualitative interpretation. In most of the proposed SLCA methods occupational safety is however measured using a quantitative approach, which is identical or very close to that used in LCA (Jørgensen et al. 2008).

The benefits of using SLCA framework for studying occupational safety is that it enables a more comprehensive view of the subject. The drawback then again is that the data collection is more complex than within LCA framework, and also that the combination of occupational safety with environmental impacts cannot necessarily be done (Jørgensen et al. 2008). Approaches for overcoming the latter issue have been presented in the form on life cycle sustainability assessment (LCSA), which however is far from being a widespread – let alone standardized – tool.

4.3.3 Occupational safety issues studied in LCA and SLCA

The scope of occupational safety issues included in the LCA framework varies greatly between different case studies. Most of the case studies based on LCA framework have focused on occupational accidents. Some studies have included both fatal and non-fatal accidents, while others have concentrated only on fatal accidents. A number of studies have also included other occupational safety issues, mainly exposure to hazardous substances. The methodology recommended by Schimdt and colleagues (2004) for example covers ten different occupational health and safety issues, while Pettersen and Hertwich (2008) for example cover only fatal and non-fatal occupational accidents. A summary of the number of issues covered by selected methods is given in table 4.2.

Most SLCA methodologies consider a far broader scope of occupational safety issues than LCA methodologies: different SLCA methods cover up to 17 indicators for physical, physiological and organizational working conditions (Jørgensen et al. 2008). This naturally gives a more comprehensive view on occupational safety, but comes at the price of increased work load during inventory analysis.

Table 4.2. *LCA methods and case studies covering occupational health and/or safety*

Method	Types of accidents covered (according to i.e. severity of accident)	Types of diseases covered (according to i.e. type of disease)
Ancona et al. 2010	3, compiled to three different indicators (YLL, DALY and cases of accidents)	0
Hofstetter & Norris 2003	2, compiled to one indicator (DALY)	2, compiled to one indicator (DALY)
Kim & Hur 2009	15, compiled to one indicator (lost work days)	7, complied to one indicator (lost work days)
Koneczny & Pennington 2007	4, compiled to one indicator (fatal accident equivalents)	0
PE International 2012	2, compiled to two indicators (fatal accidents and non-fatal accidents)	0
Pettersen & Hertwich 2008	2, compiled to one indicator (DALY)	0
Schmidt et al. 2004	10, compiled to two indicators (fatal accidents and non-fatal accidents)	8

A dimension of occupational safety that has not been covered is the safety issues related to commuting. According to the official Finnish statistics, accidents related to commuting account for ca. 15% of non-fatal and 25% of fatal work related accidents in Finland (Statistics Finland 2011a). Some SLCA methodologies have approached the issue indirectly through incorporating the distance to workplace as a societal indicator. This does not however fully cover the safety issues related to commuting, indicating a clear need for further studies.

4.3.4 Methods for inventorying occupational safety issues

Besides the scope of occupational safety, also the methods for the inventory analysis vary between different methodologies and case studies. They can be roughly divided into three groups: quantitative, semi-quantitative and qualitative methods. Quantitative methods can be further grouped into subdivisions based on the level of aggregation of data, types of occupational accidents included in the analysis, and the way occupational impacts in the supply chain are accounted for (Hofstetter & Norris 2003).

Difference can be made between the existing methodologies also based on the needed input data (Hofstetter & Norris 2003). As described earlier, some methods focus merely on fatal accidents while others take into account also non-fatal accidents or even occupational diseases (e.g. Kim & Hur 2009; Hofstetter & Norris 2003). Also the level of aggregation of data varies: some studies use aggregated data that combines a variety of industrial activities into a single industry sector (branch or screening method) while some use data specific for a single process or company (process method) (Kim & Hur 2009; Hofstetter & Norris 2003). With the process method more accurate results can be achieved, but the effort required for the collection of data is respectively significantly higher than in the branch method (Hofstetter & Norris 2003).

Quantitative methods incorporating occupational accidents often approach the issue by relating the amount of accidents to the economic output of a given sector or company. Following this approach, the amount of accidents related to a given amount of good is calculated by first dividing the total amount of accidents by the economic value of company's or sector's etc output and by multiplying it by the economic value of the good. (Hofstetter & Norris 2003; Schmidt et al. 2004)

Another approach is to use accident frequencies and working time related to the production of good as a basis for the inventory. This approach is also indirectly linked to the economic output, as the amount of working time correlates with the economic output. (PE International 2012)

As always with LCA, the accuracy of results conflicts the ease of carrying out an LCA study. Most studies therefore resort to the use of average data. In the case of occupational safety, this can however result in severely inaccurate and even misleading results: occupational safety is – unlike many environmental impacts – a result of the company's conduct rather than the nature of the individual processes. Two companies producing the same products, operating in the same geographical region and even having similar environmental impacts may have completely different social impacts, which makes the use of average data impossible of or at least difficult. In order to achieve accurate results, company or even site specific data is therefore proposed to be used. (Jørgensen et al. 2008)

4.4 Applicable approach for Metso Power

4.4.1 Possibility of including occupational safety in LCA

Studying occupational safety within the LCA framework is possible in general as discussed in chapters 4.1 and 4.3. The general motivators for including occupational safety into the LCA framework are in many cases similar to those of Metso Power. There are no technical or methodological barriers that would conflict the purposes of Metso Power. They are in fact something that the LCA is originally intended for.

The issue has been approached through both the LCA and SLCA framework, and methods that should suit also the needs of Metso Power have been proposed for both approaches. Both approaches have their pros and cons. At the moment, there is no clear cut answer if the cons of either one of the approaches are actually greater than the pros, or vice versa. The discussion however makes is clear that there are a lot of problems that have not yet been sufficiently answered. As there are no clear technical barriers for the inclusion but a lot of motivators for striving towards it, it is obvious that the inclusion is at least something worth testing. Using the words of Klöpffer (2008), *"the global situation is worsening at such a pace that we cannot wait until science will have studied all details of possible future developments, a state which will never be reached and is even unthinkable to most of us"*. It is indeed necessary to identify the most promising existing practices and use them instead of waiting for the "perfect tool", as stated also by the European Commission (2007).

With all this said, **it is technically possible to study occupational safety within the LCA framework –** also from the perspective of Metso Power. There are even a number of different approaches, from which to choose the most appropriate one. Unfortunately, there are also a number of drawbacks, which have to be evaluated. All in all, the feasibility has to be answered through the latter case study taking into account both the resources and time needed for carrying out the assessment, reliability of the information provided by it, and the usability of the information.

4.4.2 LCA or SLCA?

Metso launched an LCA pilot project in 2010 to boost its competence in LCA and to identify the best ways to carry out the assessments. During the course of the project, the framework set in ISO 14040-14044 was discovered to be the best approach for Metso. Number of drivers supported this decision, among which were the public acceptance of the approach and widespread technical and methodological support.

When determining the best approach for studying occupational safety within LCA framework, it is essential that the same aspects are paid attention to. In addition, one has to avoid taking a path that conflicts the existing procedures. Given the fact that the SLCA methodology is just under development and that there is very little technical support for its implementation, it is very challenging to resort to it in an industrial environment where the ease of use is one of the key drivers. Although SLCA is often referred to as an interesting and important development step both among industrial and academic users, it is still far from being something that can be easily used.

Another issue that hinders the usability of SLCA framework in this feasibility study is the scope of SLCA. When done “by the book”, SLCA should cover five impact categories consisting of altogether 31 subcategories. It is obvious that this kind of coverage cannot be achieved within this study.

LCA framework on the other hand is already well established. There are lots of supporting technical solutions, databases and case studies which guide practitioners during both the implementation of the method and its use. Therefore, LCA is for the meantime more suitable method for industrial users that cannot put a lot of effort in creating own methodologies and extensive databases.

A further relevant question is however whether or not it actually makes a difference, if the occupational safety is included in the SLCA or LCA framework. The focus on only a single subcategory is clearly conflicting the purpose of SLCA framework, but on the other hand, it is common for SLCA case studies that they only focus on part of the categories proposed by UNEP.[8] So is the definition, under which framework the accidents are studied actually relevant? To some degree yes, but it is still required to be able to determine which standards are followed (if any).

In the future both SLCA and LCSA will most likely gain more support. This can already be seen, as attempts at creating kinds of standardization (or at least a comprehensive set of guidelines) have been made and the first case studies have been carried out. When the technical support is available in the form of software and databases, it is likely that the expansion of LCA framework towards SLCA and eventually LCSA will be a wise step for industrial users as well. Applying the LCA framework for occupational safety up to then shouldn’t however cause any problems in the possible future transition process, as the SLCA methodology is built around the LCA framework.

4.4.3 Recommendations for LCIA and LCI methodology

4.4.3.1 Qualitative vs. quantitative methods

LCA is determined as a quantitative tool in the ISO 14040 and 14044. Qualitative methods are none the less used for simplified LCAs, and are one of the key aspects of life cycle thinking. Qualitative methods make it possible to overcome many issues related to data availability and accuracy. On the other hand, the use of qualitative information may result in drastic loss of data.

[8] Judging based on case studies presented in 6th SETAC world congress in 2012.

Carrying out an LCA according to ISO 14040-14044 is not possible using qualitative methods (ISO 14040; ISO 14044). Qualitative methods are also not suitable for marketing purposes, and do not therefore support all the purposes of this study (Jensen et al. 1997, pp. 30). In addition, qualitative methods and simplified LCA methods in general should be used only if sufficient information regarding the studied product system exists (Antikainen et al. 2012, pp. 37-40). As this is not the case, it is necessary to start with quantitative methods (even if they might not provide one with accurate answers due to inaccurate inventory data). Based on this, information can be obtained that enables the use of qualitative life cycle thinking.

4.4.3.2 Recommendations regarding scope and category indicators

As discussed in chapter 4.3, both occupational accidents and diseases can be studied within LCA framework and there are even ready methods supporting their inclusion into the framework. Most commonly covered safety issues are fatal and non-fatal accidents, which are in some cases subcategorized according to their severity. The coverage of health issues varies greatly between different methods. The methods proposed by Schmidt and colleagues (2004), and Kim and Hur (2009) cover a set of typical occupational illnesses while the method proposed by Hofstetter and Norris covers only the two broad groups of fatal and non-fatal illness cases.

When determining which method (regarding both impact assessment and the choice over studied health and safety issues) would best suit Metso Power, four different factors have to be taken into account:

1. Availability of data
2. Ease of use
3. Sensitivity of data and results
4. Intelligibility of the results

In addition to the above listed factors, one has to consider the general requirements set in the ISO standards for inventory analysis and impact assessment. The impact assessment methods, if used in the study, should be scientifically and technically valid, and internationally accepted. (ISO 14044)

The first issue is the **availability of data**: generally most of the time used for LCA studies is needed for collecting the necessary data. This has been the case also for Metso. It is therefore necessary to use a method that is supported by existing databases that can be used for Metso’s products. Most of the case studies and methods do not however provide one with such average data. Even if some average data is included, it is usually gathered outside of Europe and is therefore not necessarily suitable for this study. Taking into account the availability of data, the choice is limited to the methods proposed by Schmidt and colleagues (2004) and PE International (2012), both of which provide one with a database of occupational health and safety issues.

The second aspect to be considered is the **ease of use**. This means both that there are technical solutions supporting the implementation of the method, and that new data can be easily created when necessary. The existence of technical solutions supports the use of PE International's (2012) method: data created following the method is readily available in the LCA tool GaBi 5 used by Metso. On the other hand, neither the method proposed by Schmidt and colleagues (2004) or PE International (2012) fully supports the creation of new data: PE International's method follows the classification rules applied by the U.S department of labor, which differs from those used in the European Union and in Finland. The classification rules applied by Schmidt and colleagues (2004) then again are somewhat unclear.

Another important issue regarding the ease of use is the practical calculation approach: the PE International's (2012) method the amount of occupational accidents is calculated by multiplying the working time associated with the production of good by the accident frequency. The method proposed by Schmidt and colleagues (2004) on the other hand is more straightforward: according to the method, the accidents related to the production of given amount of good are calculated by dividing the total number of accidents in the specific sector by the total production output of the sector. This is a bit more challenging task, and in fact is recommended to be carried out by a professional statistician from a governmental statistical agency (Schimdt et al. 2004).

All in all, given the fact that the classification rules used by PE International are well documented, new data can be easily created and that the data is readily integrated in the software, it is recommended to use the method for inventorying the occupational health and safety issues. In practice, this means that **the study will focus on fatal and non-fatal accidents only**, and that **the amount of accidents is calculated by multiplying the average working time by the specific accident frequency**. A further decision has to be made, in what depth the data is to be acquired: some studies utilizing this or similar methods use aggregated data that combines a variety of industrial activities into a single industry sector to determine the accident frequency (branch or screening method) while others use data specific for a single process or company (process method) (Kim & Hur 2009; Hofstetter & Norris 2003). With the process method more accurate results can be achieved, but the effort required for the collection of data is respectively significantly higher than in the branch method (Hofstetter & Norris 2003). In the case of Metso Power, the studied product systems are generally very complex and consist of a vast number of individual processes. In order to simplify the data collection, the screening method should be used as primary approach, and the process method resorted to only if a single process is proven to account for a significant share of all accidents. Whether or not this is a feasible approach to study any social issues has been questioned (Jørgensen et al. 2008). At the moment there is no definite answer to this, but as many studies have approached the issue through screening method, it is considered applicable also for this study.

An interesting issue not covered before is the role played by accidents related to commuting. This data is also not included in the PE International's database. As one of the goals of this study is on the other hand to study the importance of studying occupational safety issues within LCA framework, and as accidents related to commuting account for a significant share of all work related accidents, it might be misleading not to consider them. **The accidents related to commuting are therefore included in this study alongside occupational accidents.** The amount of those accidents is calculated following the same approach as in the case of occupational accidents. As the GaBi databases do not include commuting accidents, their amounts have to be therefore calculated. This should not however be too complicating, as the amounts of commuting accidents can be calculated similarly as the amounts of occupational accidents using for example the working time data given in GaBi.

The third issue to be kept in mind is the **sensitivity of results**: if the inventory analysis and impact assessment methods are highly sensitive, the results can be misleading. The results of inventory analysis are in many cases extremely vulnerable to variation due to different technologies and environmental performance of companies. According to Finnveden and Lindfors (1998), the LCI results of different datasets can vary by a factor of up to 100 in the case of a single elementary flow. A more recent study by Winkler (2005) showed that the outputs of a single elementary flow can vary by a factor of up to 15 between different datasets.

Impact assessment generally provides one with a solution for decreasing the variation in results (Finnveden & Lindfors 1998). This is also the case for occupational accidents and especially non-fatal occupational accidents. In the GaBi's database for example, non-fatal accidents include all accidents leading to time away from work or restricted working ability. On the other hand, the Finnish statistics contain detailed data only regarding accidents leading to over three days absence from work, while the less severe accidents have to be estimated based on some average data. This estimate together with the very likely underreporting of minor accidents can lead to clear error in the amount of non-fatal accidents.

Using an impact assessment method however decreases the significance of this error: when calculating DALY values for instance, the importance of less severe accidents is decreased as both their disability weight and duration are minor compared to better known severe accidents. In fact, while the amount of accidents is dominated by less severe accidents, the DALY value is in fact dominated by severe accidents leading to long term or even permanent disability (Dupré 2001; Statistics Finland 2011a; Hofstetter & Norris 2003).

Although impact assessment exposes the results of the study to a set of sources of error, the benefits regarding the accuracy of results can be considered to be greater than the drawbacks. It is therefore recommended to use some LCIA method for assessing the impacts of occupational accidents. The most widely used method is to use DALY as category indicator, but also other approaches exist.

The final issue that has to be paid attention to is the **intelligibility of the results**. When presenting the results of Metso's LCA pilots, two questions were presented repeatedly: what does this mean, and how significant is this result. The meaning of accident data, as it is reported following the PE International's (2012) method, is easier to understand than the meaning of many other LCIA indicators. The significance is however a lot more problematic to define: how significant is it, if the disposal of one ton waste is associated with for example 0,005 fatal accidents? Naturally, only zero accidents is sustainable and this is also something Metso is striving for. Even the occurrence of a single one accident is a warning signal, and if there is a proven risk for an accident occurring, this should not be tolerated.

The above mentioned series of questions and emotions states that the occupational accidents are indeed something that is taken very emotionally. In such case, the evaluation of the results is always based on personal preferences. The second working group on LCIA by SETAC-Europe proposed that in such cases the indicators should be chosen at the category endpoints (Udo de Haes et al 1999a). This can make it easier to overcome the personal preferences and help keep in mind that the expressed impacts are not absolute impacts.

The same working group also proposed that characterization factors at endpoint level should be defined for categories with impacts on human health to enable their mutual comparison (Udo de Haes et al 1999a). The mutual comparison of impacts is another way of improving the intelligibility of the results: aggregating the results into a single score makes it that it is easier to track any trade-offs. It also makes it easier to understand, if a single source of environmental impacts or impacts on human health (for example occupational accidents) is a relevant contributor compared to other sources of impacts.

In order to make it possible to compare all impacts on human health, one has to choose an indicator that is already used for other impact bath ways. The summary in table 4.1 in chapter 4.3.1 reveals that DALY is the only suitable category indicator as long as no new environmental category indicators are to be defined.

Considering all four factors, DALY seems the best approach for measuring the impacts of occupational accidents. With the indicator being already used in a numerous LCIA methods and supported by the World Health Organization there is also no risk of it conflicting the requirements set in the ISO 14044. **It is therefore recommended that DALY is used as primary metric for assessing the impacts occupational accidents within LCA framework**. However, the recommended inventory analysis method is based on measuring impacts at midpoint level, and it is generally recommended to measure impacts also on midpoint level parallel to endpoint level (Udo de Haes et al 1999a; Baer et al. 2000). Therefore it is also recommended that cases of fatal and non-fatal accidents are taken as supporting category indicators.

4.4.3.3 Method for calculating the inventory data

Readily available inventory data can be found for most of the background processes in the GaBi databases. Data for the foreground processes as well as some background processes is however not available in the databases, and has to be therefore acquired from other sources. When collecting the data, two types of data are needed: the average working time associated with the value added (or amount of good produced), and the average accident frequency for the specific process.

The working time is recommended to be collected specifically for each process. This in many cases requires the use of some allocation method, as the working times are in many cases available for a set of processes only. The allocation method should be in line with the general allocation method applied for the specific study.

Accident frequencies are commonly reported on national level and in many cases also on corporate level. While dealing with the accident frequencies, the consistency of data has to be paid attention to. This is extremely important especially in cases, where data is collected from numerous sources. One of the primary issues to be kept in mind is that the accident frequency varies not only between different industry sectors, but also between different countries. **It is recommended based on this to use data from the specific country and industry sector**.

Acquiring accident data for a large number of countries and especially for developing countries can be difficult and very time consuming. In some cases the data may not even exist. In such cases the accident frequency for a specific nation can be calculated by multiplying the industry specific accident frequencies in a reference geographical with a correction factor for the specific country. The correction factor (G) is calculated using equation (4).

$$G = \frac{R_{a,c}/WH_c}{R_{a,RE}/WH_{RE}} \qquad (4)$$

In the above equation, $R_{a,c}$ is the average rate of occupational accidents in the specific country as reported by Hämäläinen and colleagues (2006), and WH_c is the average annual working time. $R_{a,RE}$ then again is the rate of occupational accidents and WH_{RE} the average annual working time in the reference area or country.

Besides the geographical location, also the classification principles and coverage of accidents have to be paid attention to: the data included in GaBi databases is calculated based on initial data by the United States Department of Labor’s Bureau of Labor Statistics, which covers all recordable incidents. The Finnish and European statistics on the other hand include data regarding only that lead to at least four days away from work.

In order to guarantee that the inventory is consistent for all parts, the data may have to be modified so that it covers the same types of accidents for all parts. The statistics that cover only severe accidents (i.e. for example in the case of Finland only accidents leading to over three days away from work) have to be corrected to include also accidents leading to less severe accidents. This is done by multiplying the average accident frequency of non-fatal occupational accidents by a correction factor k, which is calculated by dividing the amount of all occupational accidents with the amount of severe accidents. If the overall amount of accidents is unknown, best estimates given in literature should be used.

As the method is based on using statistical data, the data should be collected over a period of time that is long enough for the data to be reliable. Given that some industry sectors are relatively small and serious accidents occur relatively rarely, the data should be collected over more than one year period. However, as many processes are expected to occur in the future, the data should in the same time also represent future scenario data, BAT data or most recent data (European Commission 2010d). The use of BAT data is not feasible, as the BAT level for occupational safety is zero accidents. Also using future scenario data is slightly problematic as most future scenarios are based on the assumption that the amount of occupational accidents is decreased in the future. If this does not happen, the significance of accidents is underestimated. Also basing the study on assumption that the impacts will be decreased is in conflict with the precautionary principle demanded to be followed. Therefore, most recent data is the only feasible option. **The period of time for data collection is recommended to be taken as the five most recent years for which data is available**.

4.4.3.4 Method for determining the characterization factors

The calculation of characterization factors requires that two types of information regarding occupational accidents is known:

1. For fatal accidents, the remaining life time during the time of accidents
2. For non fatal accidents, the average duration of accidents and the average disability weight of accidents

All of the above mentioned factors depend on among other factors the geographical location: in Finland for example, the average life expectancy differs from that in e.g. developing countries. Also the disability weight varies between countries, as the access to proper health care and therefore also the recovery rate is different in different countries. This affects of course also the average duration of the medical condition.

Another issue that has to be paid attention to is the fact that different industry sectors have different risk profiles. This leads to different types of injuries, and therefore also different types of disability weights and durations of medical conditions. For example, wounds and other superficial injuries, which have relatively low disability weight and recovery time, account for ca. 35% of all occupational accidents in the manufacturing industries, but only ca. 16% in the transportation sector. It is therefore recommended to develop country and sector specific characterization factors to see if the above mentioned differences are relevant regarding the outcomes of this study. For accidents included in GaBi databases the characterization factors are calculated assuming that the processes take place within the European Union.

The characterization factors have to be studied separately for fatal and non-fatal accidents. For fatal accidents the characterization factor is the average life expectancy at the time of accident, which can be calculated using equation (5) (World Health Organization 2012a).

$$Cf = \bar{A} \tag{5}$$

In equation (5) Cf is used to indicate the characterization factor for occupational accidents, and $\bar{A}$ the corresponding average life expectancy. The average life expectancy is calculated using equation (6), where $\bar{A}_{s,y}$ is the average life expectancy of males or females killed in occupational accidents during one of the reference years, $N_{s,y}$ is the corresponding amount of males or females killed in accidents, and $N_{total,y}$ the amount of both males and females killed in occupational accidents during the same year.

$$\bar{A} = \sum_s \sum_y \frac{N_{s,y} * \bar{A}_{s,y}}{N_{total,y}} \tag{6}$$

In general, the characterization factor for non-fatal occupational accidents is calculated using equation (7), where I_{total} is the total incidence of non-fatal accidents, I_i the incidence of given medical condition, DW_i its disability factor and $\overline{L_d}_i$ the average duration of the given medical condition.

$$Cnf = \overline{DW} * \overline{L_d} = \sum \left(\frac{I_i}{I_{total}} * DW_i * \overline{L_d}_i \right) \tag{7}$$

4.5 Reference data for LCI and LCIA

The drawback of the proposed LCI and LCIA methods is that they both require a lot of data to be collected. The proposed LCI method for one requires that both the working times and the accident frequencies are known. The LCIA method on the other hand requires even more detailed information: in order to calculate the characterization factors, one has to be aware of the average healing time and the type of medical condition resulting from the accident.

Especially the LCI stage is extremely laborious even as such, and requiring that even more data is collected can easily lead to it becoming frustratingly complicated. The same applies also for the LCIA stage: in case the characterization factors have to be calculated and documented individually for each study, the LCIA stage is in risk of becoming as or even more laborious than the LCI stage. In order to avoid this from happening, some reference data is given in this chapter that can be used as a starting point for later studies. **The data will be collected following the branch (or screening) method, and should therefore be used only for screening level assessments or for more detailed assessments in case it is of low relative importance**.

The reference data given here is collected so that it is in line with the boundary conditions of the case study. In practice this means that the data is collected from the geographical areas and for the processes that are relevant considering the case study. Also the period of time from which the data is collected has to be applicable considering the case study. In case data that meets different boundary conditions is needed, it has to be collected separately.

4.5.1 Reference data for life cycle inventory analysis

To reduce the efforts required for the inventory analysis, data has been collected only for Finland and EU average, where most of the fore- and background processes are assumed to take place. Accident frequencies for Finland have been taken from the statistics published by the Federation of accident insurance institutions. For the EU area, which is approximated by EU-15 countries, accident frequencies published by Eurostat have been used[9]. Here the industry sectors are limited to NACE A-F and H sectors, which are the primary sectors affected by processes included in the case study. The explanations of NACE A-F and H sectors are given in table 4.3.

The EU-15 data should be used for all processes taking place in Europe as a first approximation. More accurate data should then be used in case the process takes place outside of Europe and/or is expected to be significant regarding the outcomes of the study. In such case country specific accident frequencies should be used. The country specific accident frequency can be taken from national statistics, or calculated using equation (4). For this study, EU-15 area is taken as reference area.

Only the accident frequencies are discussed in this chapter. The other half of inventory data needed, i.e. the working time associated with a specific process, has to be obtained specifically for each process.

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[9] In this study EU area will be approximated by EU-15 countries, i.e. Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden and United Kingdom due to limitations in the availability of data.

4.5.1.1 Accident frequencies for Finland

Accident frequencies **for non-fatal occupational and commuting accidents** in Finland are calculated using equation 4 as an average of years 2005-2009 unless otherwise mentioned. In equation (8), $N\dot{F}A$ is the average corrected accident frequency[10], $n\dot{f}a_y$ reported accident frequency in year y, b the first year of the studied period and f the last, and k_y the correction factor for the specific year. A five year average is used to ensure that the data is statistically valid. The period of time is chosen based on the availability of data: data is available only until 2009, and data older than 2005 has been collected partially following different reporting principles. The accident frequencies for selected Finnish industry sectors have been given in table 4.3.

$$N\dot{F}A = \frac{\sum_b^f k_y * n\dot{f}a_y}{f-b} \qquad (8)$$

Table 4.3. *Accident frequencies reported by the Federation of accident insurance institutions for non-fatal occupational and commuting accidents, and the corrected accident frequencies (covering also accidents leading to less than four days away from work) in Finland. (Federation of accident insurance institutions 2011)*

Industry sector	Accident frequency for accidents leading to over three days away from work (average 2005-2009)		Corrected accident frequency for all accidents (average 2005-2009)	
	Occupational accidents	**Commuting accidents**	**Occupational accidents**	**Commuting accidents**
Agriculture, forestry and fishing (NACE2 A)	14,6	0,9	32,8	1,9
Mining and quarrying (NACE2 B)	16,6	2,7[1]	36,9	5,5
Manufacturing industry (NACE2 C)	20,3	2,3	45,4	4,8
Electricity, gas, steam and air conditioning supply (NACE2 D)	14,2	2,5[2]	31,6	5,1
Water supply; sewerage, waste management and remediation activities (NACE2 E)	26,9	2,7[1]	60,2	5,5
Construction (NACE2 F)	38,1	1,9	85,2	3,8
Transportation and storage (NACE2 H)	28,2	2,7	63,0	5,4
National average	15,2	2,7	34,0	5,5

[1]National average used as no sector specific data is available
[2]Years 2006, 2008 and 2009 only

[10] $N\dot{F}A$ is used to denote the accident frequency for non-fatal occupational accidents, and $N\dot{F}AC$ the accident frequency for non-fatal commuting accidents. Here only the equation for occupational accidents is given. The equation for commuting accidents is similar with the exception of different symbols for accident frequency.

Calculating the accident frequencies for **fatal accidents** is a bit more complicated, since their amounts have been reported for the industry sectors differentiated in table 4.3 only for years 2008 and 2009. Data for earlier years has been reported using NACE rev.1 classification (referred to as NACE1), which is slightly different from the NACE rev. 2 classification (referred to as NACE2) used for non-fatal accidents and for fatal accidents after 2008. Data prior to 2008 cannot therefore be directly used. On the other hand, using data from just two years could result in significant inaccuracy, as the sample sizes are in most cases very small.

To overcome this limitation, the amounts of fatal occupational accidents have been calculated using equation (9) for years 2006-2007 (2005 has been left out due to lack of data regarding the amount of fatal accidents in different industry sectors). In equation (9), FA denotes the amount of fatal and nfa the (non-corrected) amount of non-fatal accidents in the specific NACE2 or best representative NACE1 industry sector. The Finnish average values have been used for both FA and nfa in the case of commuting accidents. $\dot{FA}$ and $n\dot{f}a$ denote the corresponding accident frequencies in the specific NACE2 industry sectors. The accident frequency used for this study is then calculated as an average of years 2006-2009. The results are given in table 4.4.

$$\dot{FA}_{NACE2} = \frac{FA_{NACEi}}{nfa_{NACEi}} * n\dot{f}a_{NACE2} \tag{9}$$

In addition to the correction to include accidents resulting in short absence from work above, some studies suggest that the accident frequencies should be corrected to consider also the underreporting of accidents (e.g. Hofstetter & Norris 2003). In Finland the reporting rate has been estimated to be close to 100% (Dupré 2000), and this kind of correction is therefore not made. Also the exclusion of self employed people from the statistics should be taken into account in some cases (Hämäläinen et al. 2006). As this study focuses on accident frequencies, which are calculated by dividing the amount accidents by the working hours of the people included in the scope of the statistics, this kind of correction is not necessary.

Table 4.4. *Frequencies of fatal accidents for given industry sectors in Finland (Statistics Finland 2008a, 2009a, 2010a and 2011a; Federation of accident insurance institutions 2011).*

Industry sector	Accident frequency for fatal accidents (average 2005-2009)	
	Occupational accidents	**Commuting accidents**
Agriculture, forestry and fishing (NACE2 A for 2008-2009, NACE1 A for 2006-2007)	0,034	0,002
Mining and quarrying (NACE2 B for 2008-2009, NACE1 C for 2006-2007)	0,026	0,006
Manufacturing industry (NACE2 C for 2008-2009, NACE1 D for 2006-2007)	0,006	0,005
Electricity, gas, steam and air conditioning supply (NACE2 D for 2008-2009, NACE1 E for 2006-2007)	0,033	0,005
Water supply; sewerage, waste management and remediation activities (NACE2 E for 2008-2009, NACE1 E for 2006-2007)	0,026	0,006
Construction (NACE2 F for 2008-2009, NACE1 F for 2006-2007)	0,032	0,004
Transportation and storage (NACE2 H for 2008-2009, NACE1 I for 2006-2007)	0,039	0,006
National average	0,010	0,006

4.5.1.2 Accident frequencies for EU-15 area

Accident frequencies for EU-15 area are calculated following basically the same approach as for Finland. For EU-15 area only incident rates have however been reported, so the accident frequencies of **non-fatal occupational accidents** for a specific year have been calculated using equation (10), and the average accident frequency is taken as the average of years 2005-2008. Year 2009 has not been considered, as no data for the year is available. In the below equation, $R_{a,y}$ denotes the rate of accidents during given reference years including only accidents leading to at least four days absence from work, k_y the correction factor for the specific year and WH_y the average working time during the same reference period.

$$\dot{NFA} = k_y * 10R_{a,y}/WH_y \qquad (10)$$

The average annual working time for EU-15 area is taken as ca. 1700 hours (Cabrita & Ortigão 2011). The correction factor for all years is taken as 1,58. The correction factor is calculated assuming that 37% of all occupational accidents lead to less than four days away from work, as reported by Dupré (2000). For 2008 the incidence rate is calculated as weighted average of the incidence rates reported separately for the member countries. The weighting is done by the amount of accidents in the specific country. For other years the incidence rate is taken as reported by Eurostat (2012f).

The frequencies for **non-fatal commuting accidents** have been calculated based on data reported by Eurogip (2009a; 2010a; 2010b; 2010c; 2010d; 2011; 2012) for Belgium (years 2005-2008 considered), Germany (2005-2009), Italy (2005-2008), Austria (2006-2008), Sweden (2005-2009), France (2005-2009) and Spain (2008-2009). Other EU-15 countries have not been considered due to lack of data. For non-fatal commuting accidents the accident frequency is calculated based on accident frequency for non-fatal occupational accidents and data regarding the relative incidence of occupational and commuting accidents as expressed in equation (11). All data regarding commuting accidents is collected at national level, as no (industry) sector specific data is available.

$$N\dot{F}AC = \frac{N_{commuting}}{N_a} * k_{commuting} * N\dot{F}A \tag{11}$$

In equation (11) $N\dot{F}AC$ is used to denote the amount of commuting accidents in the listed countries, and $N_{occupational}$ the respective amount of occupational accidents and $N_{commuting}$ the amount of commuting accidents. $k_{commuting}$ is the correction factor for commuting accidents, which is calculated based on data reported by Eurogip (2010d) for France[11] and taken as 1,57.

The accident frequencies for EU-15 have been given in table 4.5. The data does not include year 2009, as no data is available for the year. Also, data for years 2005-2007 has been reported using NACE rev.1 classification, so accident frequencies for the NACE2 industry sectors for years 2005-2007 have been approximated based on the accident frequency for best representative NACE1 industry sector. Commuting accidents have been given only for EU-15 average, as industry specific data is available only for a few countries during one or two years.

[11] The correction factor is calculated based on data regarding France only as no data for other reference countries is available.

Table 4.5. *Accident frequencies reported by Eurostat (2009; 2012f; 2012g) and Eurogip for non-fatal occupational and commuting accidents (2009a; 2010a; 2010b; 2010c; 2010d; 2011; 2012), and the corrected accident frequencies (covering also accidents leading to less than four days away from work) in EU-15 area.*

Industry sector	Accident frequency for accidents leading to over three days away from work (average 2005-2008)		Corrected accident frequency for all accidents (average 2005-2008)	
	Occupational accidents	**Commuting accidents**	**Occupational accidents**	**Commuting accidents**
Agriculture, forestry and fishing (NACE2 A for 2008, NACE1 A for 2005-2007)	24,6[1]	n.d.	39,0	n.d.
Mining and quarrying (NACE2 B for 2008, NACE1 C for 2005-2007)	40,1[2]	n.d.	63,4	n.d.
Manufacturing industry (NACE2 C for 2008, NACE1 D for 2005-2007)	21,2	n.d.	33,6	n.d.
Electricity, gas, steam and air conditioning supply (NACE2 for 2008, NACE1 E for 2005-2007)	10,3	n.d.	16,3	n.d.
Water supply; sewerage, waste management and remediation activities (NACE2 E)	35,0[3]	n.d.	55,4	n.d.
Construction (NACE2 F for 2008, NACE1 F for 2005-2007)	34,7	n.d.	55,0	n.d.
Transportation and storage (NACE2 H for 2008, NACE1 I for 2005-2007)	22,9[4]	n.d.	36,9	n.d.
EU-15 average	17,5	3,1	27,9	4,8

[1]Data for 2008 is inconsistent with data for earlier years, and has not therefore been considered
[2]Data for years 2005 and 2008 only
[3]Data for 2008 only
[4]Data for UK 2008 not considered due to inconsistent reporting

Accident frequencies **for fatal accidents** have been calculated similarly as for non-fatal accidents (i.e. using equations (10) and (11)) with the exception that no correction factor is needed. The accident frequencies for fatal accidents are given in table 4.6.

Table 4.6. *Accident frequencies reported by Eurostat (2009; 2012f; 2012h) and Eurogip for fatal occupational and commuting accidents (2009a; 2010a; 2010b; 2010c; 2010d; 2011; 2012) in EU-15 area. Data for 2008 is missing for some countries and industry sectors, so the values given here have been calculated based on available data.*

Industry sector	Accident frequency for fatal accidents (average 2005-2008)	
	Occupational accidents	**Commuting accidents**
Agriculture, forestry and fishing (NACE2 A for 2008, NACE1 A for 2005-2007)	0,057[1]	n.d.
Mining and quarrying (NACE2 B for 2008, NACE1 C for 2005-2007)	0,134[2]	n.d.
Manufacturing industry (NACE2 C for 2008, NACE1 D for 2005-2007)	0,015	n.d.
Electricity, gas, steam and air conditioning supply (NACE2 D for 2008, NACE1 E for 2005-2007)	0,037	n.d.
Water supply; sewerage, waste management and remediation activities (NACE2 E for 2008, NACE1 E for 2005-2007)	0,044[3]	n.d.
Construction (NACE2 F for 2008, NACE1 F for 2005-2007)	0,050	n.d.
Transportation and storage (NACE2 H for 2008, NACE1 I for 2005-2007)	0,045[4]	n.d.
EU-15 average	0,018	0,010

[1]Data for 2008 is inconsistent with data for earlier years, and has not therefore been considered
[2]Data for years 2005 and 2008 only
[3]Data for 2008 only
[4]Data for UK 2008 not considered due to inconsistent reporting

Again, the underreporting of accidents can have an impact on the calculated accident frequencies. According to Dupré (2000) the reporting in EU-15 countries covered ca. 88% of occupational accidents leading to at least four days away from work in 1999. Hämäläinen and colleagues (2006) on the other hand suggest that ca. 95% of occupational accidents are reported in the EU. The underreporting of accidents has however been taken into account in the Eurostat data, and no additional corrections are therefore needed (Eurostat 2011).

4.5.2 Characterization factors for LCIA

The characterization factors are defined here for the same industry sectors and geographical areas as for which the inventory data is collected in previous chapter. For non-fatal accidents the characterization factors have been calculated separately for each industry sector. No differences between different industry sectors have been considered in the case of fatal occupational accidents due to both limited availability of data and the small sample size for specific industry sectors.

Accidents leading to less than four days away from work have been treated as a group of unspecified injuries. The disability weight for them is taken as 0,064 as suggested by

Forbes and colleagues (2006) for unspecified injuries, and the average time spent away from work as ca. 3 days. For more severe accidents the duration is calculated specifically for the each type of medical condition. The disability factors for severe accidents have been taken as reported by Forbes and colleagues (2006) for each type of medical condition. It should be noted that the disability weights specific to a single country or region may not be applicable worldwide (Begg & Tomijima 2000). It can however be safely assumed that the level of medical care is sufficiently similar in Australia as in Finland, and the values reported by Forbes and colleagues can therefore be assumed sufficiently accurate.

The durations of disabilities (i.e. healing times) have been calculated using equation (12). In equation (12), n_t is the amount of occupational accidents with an average absence from work of L_{d_t} days leading to a given medical condition, and n_{total} is the total amount of occupational accidents leading to a given medical condition. The average absence from work, L_{d_t}, is taken as the mean value of each reported interval (for example, for accidents causing absence from work of 31-90 days the average duration is taken as 60,5 days). The actual healing time is assumed to be twice as long as the time spent away from work as suggested by Hofstetter and Norris (2003) for all accidents except those leading to permanent retirement. For accidents leading to retirement the average duration ($L_{d_{t>365}}$) is taken as the life expectancy at the time of non-fatal accident. Also, for all accidents resulting in amputations the duration is taken as the remaining life time as suggested by both Begg and Tomijima (2000), and Forbes and colleagues (2006). In addition, Begg and Tomijima (2000) suggest that the duration for burns should also be taken as the remaining life time, but since the statistics do not differentiate burns from e.g. frostbites, this has not been done. The life expectancy (i.e. the duration of accidents leading to permanent disability or retirement) is calculated using equation (6).

$$\overline{L_d} = \frac{2*(\sum n_{0\leq t\leq 365}*L_{d_{0\leq t\leq 365}})+n_{t>365}*L_{d_{t>365}}}{n_{total}} \qquad (12)$$

4.5.2.1.1 Characterization factors for occupational accidents in Finland

The characterization factor for **fatal occupational accidents** in Finland is calculated using equation (7). The initial values used for calculating the average life expectancy are presented in appendix A. Assigning the initial values to equations (5) and (6) results in life expectancy of 38,8 years at the time of a fatal occupational accident, which is used for all fatal occupational accidents independent of industry sector.

The characterization factors for **non-fatal accidents** are calculated using equation (7). Accidents leading to less than four days away from work have been treated as a group of unspecified injuries. For more severe accidents the duration is calculated specifically for the each type of medical condition using equation (12). The initial data needed is taken from Eurostat (2012a and 2012b) and Federation of Accident Insurance Institutions (2011) and presented in appendix A for relevant parts. Data from 2008 is used as no other data is available. The same average duration for each type of disability is used independent of the industry sector. The life expectancy at the time of non-fatal accident is calculated using equation (6) for the sex and age distribution of non-fatal occupational accidents in years 2005-2009 and taken as 39 years. This is also the duration for accidents leading to retirement ($L_{d_{t>365}}$ in equation (12)).

Industry specific shares of medical conditions resulting from occupational accidents (I_i in equation (7)) are taken as reported by Eurostat (2012a, 2012b and 2012c). It has been assumed that the share of accidents leading to less than four days away from work is the same for all industry sectors (54,7% as calculated based on Federation of accident insurance institutions (2011)) as no more detailed data is available. For the parts data regarding the specific industry sector is not available, the shares of medical conditions have been estimated based on data regarding Finnish average or EU-15 countries. For Finland the base year is taken as 2008 as no data from other years is available, and for EU-15 countries as years 2005-2007. The shares of medical conditions for the national average have been calculated based on data from years 2005-2009 as reported by the Federation of accident insurance institutions (2011). The average shares of injuries resulting from occupational accidents have been given in appendix A.

The disability weight for accidents leading to less than four days away from work is taken as 0,064 (as suggested by Forbes and colleagues (2006) for unspecified injuries) and the average time spent away from work as ca. 3 days. The disability factors for more severe accidents have been taken as reported by Forbes and colleagues (2006) for each type of medical condition. It should be noted that the disability weights specific to a single country or region may not be applicable worldwide (Begg & Tomijima 2000). It can however be safely assumed that the level of medical care is sufficiently similar in Australia as in Finland, and the values reported by Forbes and colleagues can therefore be assumed sufficiently accurate.

The calculated durations and the disability weights reported in literature are given in table 4.7. Also the shares of medical conditions on national level have been given in table 4.7. More detailed data regarding the calculation of the durations and the shares of medical conditions on industry level is presented in appendix A.

Table 4.7. *Average durations and disability weights for medical conditions resulting from non-fatal occupational accidents in Finland*

Condition	**Disability weight**	**Duration, calculated**	**Duration, this study**
Open wound	0,118	0,13	0,13
Superficial injury	0,013	0,13	0,13
Bone fractures	0,143	0,73	0,73
Dislocation	0,132	0,25	0,25
Sprains and strains	0,067	0,26	0,26
Traumatic amputations (Loss of body parts)	0,205	1,38	39,34[1]
Intracranial injury, incl. concussion	0,359	0,26	0,26
Internal injury	0,209	0,21	0,21
Burns, scalds and frostbites	0,030	0,13	0,13
Poisonings and infections	0,608	0,26	0,26
Drownings and asphyxiations	0,064[2]	0,03	0,03
Effects of sound, vibration and pressure	0,083	0,09	0,09
Effects of temperature, light and radiation	0,358	0,42	0,42
Shocks	0,064[2]	0,19	0,19
Multiple injuries	0,122	0,93	0,93
Other not elsewhere mentioned	0,064[2]	0,39	0,39
Unspecified	0,064[2]	0,31	0,31
Unspecified, less than four days away from work	0,064[2]	N/A	0,02

[1]Life expectancy at the time of accident. Calculated using equation 5 and data published by Federation of Accident Insurance Institutions (2011) and Eurostat (2012d).
[2]Disability weight for unspecified medical conditions according to Forbes et al. (2006)

Assigning the durations and disability weights given in table 4.7, and the industry specific shares of each medical condition given in appendix A to equation 6 results in characterization factors given in table 4.8. The characterization factors are given for NACE2 A-F and H sectors and national average.

Table 4.8. *Characterization factors for non-fatal occupational accidents in Finland*

Industry sector	$\boldsymbol{Cnf}$
Agriculture, forestry and fishing (NACE2 A)	0,0342
Mining and quarrying (NACE2 B)	0,0354
Manufacturing industry (NACE2 C)	0,0397
Electricity, gas, steam and air conditioning supply (NACE2 D)	0,0255
Water supply; sewerage, waste management and remediation activities (NACE2 E)	0,0238
Construction (NACE2 F)	0,0333
Transportation and storage (NACE2 H)	0,0254
National average	0,0300

The values of characterization factors vary slightly between different industry sectors. It can be assumed that the actual values differ more from one another than the calculated values, since different working conditions and the resulting differences in the nature and severity of injuries are taken into account only partially. Industry specific data has in many cases been completed with average data. The calculated values are on the other hand in the neighborhood of the characterization factor (0,033) given in a report by Koneczny and Pennington (2007, pp. 67), which suggests that they are valid and can be used for the impact assessment. The differences between the calculated values and those reported by Koneczny and Pennington (2007, pp. 67) can very well result from using data from different years and different geographical regions. Also the statistics pose various possible sources of error: for example the days away from work can in many cases differ from the actual healing time and some types of injury may be underreported or misclassified.

4.5.2.1.2 Characterization factors for occupational accidents in EU

The occupational accidents inventoried based on data given in GaBi databases are assumed to take place in the European Union, which is approximated based on EU-15 countries due to limitations in data availability. The characterization factors for them are calculated following mainly the same approach as described in previous chapter. However, there are severe gaps in the data that is used for calculating the characterization factors: the duration of accidents is mainly unknown (for example, the duration of 99% of accidents taking place in both UK and Germany in 2008 is unknown). Also, the statistics include data regarding only accidents that lead to over three days absence from work. Furthermore, the statistics published by Eurostat include data that is needed to calculate the characterization factors for the year 2008 only, so the characterization factors have to be calculated based on a single year only (as is done for most parts also in the case of Finland).

For **fatal accidents** in EU-15 area the characterization factor is 33,09. The characterization factor is calculated using the approach discussed in the previous chapter.

For **non-fatal occupational accidents** the same correction approach as used for calculating Finnish data is used also for EU-15 countries: it has been assumed based on data reported by Dupré (2000) that 37% of all occupational accidents lead to less than four days absence from work and are therefore not included in the statistics. These accidents have been treated as a group of unspecified accidents, as in the case of Finland using the same disability weight and duration. For the other accidents, the disability weight presented by Forbes and colleagues (2006) are used. The duration for a significant share of accidents has not been reported in the Eurostat database for 2008. Therefore, the durations of accidents resulting in different medical conditions are calculated based on data reported by European Commission (2009) for 2005. The duration (i.e. actual healing time) is again assumed to be twice the time spent away from work. For amputations, the duration is taken as the remaining life time. The average durations of accidents are given in table 4.9 along with the disability weights.

The shares of different medical conditions have been calculated similarly as for Finland based on data reported by Eurostat (2012c) for 2008. In case data for 2008 is not available, the shares have been calculated based on data reported for years 2005-2007. The average shares of injuries resulting from occupational accidents have been given in appendix A for each industry sector.

Table 4.9. *Average shares and durations for medical conditions resulting from non-fatal occupational accidents in EU-15 area.*

Condition	**Disability weight**	**Duration, calculated**	**Duration, this study**
Open wound	0,118	0,13	0,13
Superficial injury	0,013	0,13	0,13
Bone fractures	0,143	0,37	0,37
Dislocation	0,132	0,16	0,16
Sprains and strains	0,067	0,15	0,15
Traumatic amputations (Loss of body parts)	0,205	0,48	41,28[1]
Intracranial injury, incl. concussion	0,359	0,16	0,16
Internal injury	0,209	0,14	0,14
Burns, scalds and frostbites	0,030	0,12	0,12
Poisonings and infections	0,608	0,13	0,13
Drownings and asphyxiations	0,064[2]	0,13	0,13
Effects of sound, vibration and pressure	0,083	0,10	0,10
Effects of temperature, light and radiation	0,358	0,11	0,11
Shocks	0,064[2]	0,17	0,17
Multiple injuries	0,122	0,24	0,24
Other not elsewhere mentioned	0,064[2]	0,17	0,17
Unspecified	0,064[2]	N/A	N/A
Unspecified, less than four days away from work	0,064[2]	0,02[3]	0,02

[1] Life expectancy at the time of accident. Calculated for EU-15 area using equation 5 and data published by Eurostat (2012b, 2012d, 2012e).
[2] Disability weight for unspecified medical conditions according to Forbes et al. (2006)
[3] The same as for Finland

Assigning the values given in table 4.9 and appendix A to equation (7) results in characterization factors given in table 4.10.

Table 4.10. *Characterization factors for non-fatal occupational accidents in EU-15 area*

Industry sector	$\boldsymbol{Cnf}$
Agriculture, forestry and fishing (NACE2 A)	0,0443
Mining and quarrying (NACE2 B)	0,0377
Manufacturing industry (NACE2 C)	0,0425
Electricity, gas, steam and air conditioning supply (NACE2 D)	0,0174
Water supply; sewerage, waste management and remediation activities (NACE2 E)	0,0289
Construction (NACE2 F)	0,0310
Transportation and storage (NACE2 H)	0,0228
National average	0,0283

As in the case of Finland, the values of characterization factors vary between different industry sectors. The characterization factors are the same magnitude as for Finland and as reported by Koneczny and Pennington (2007, pp. 67). There are some differences in the characterization factors, which result mainly from slightly different durations, and above all shares of different medical conditions. The biggest differences between the characterization factors for Finland and EU-15 are in NACE2 A and D sectors. A comparison of characterization factors between Finland, EU-15 and those reported by Koneczny and Pennington (2007, pp. 67) is given in figure 4.3.

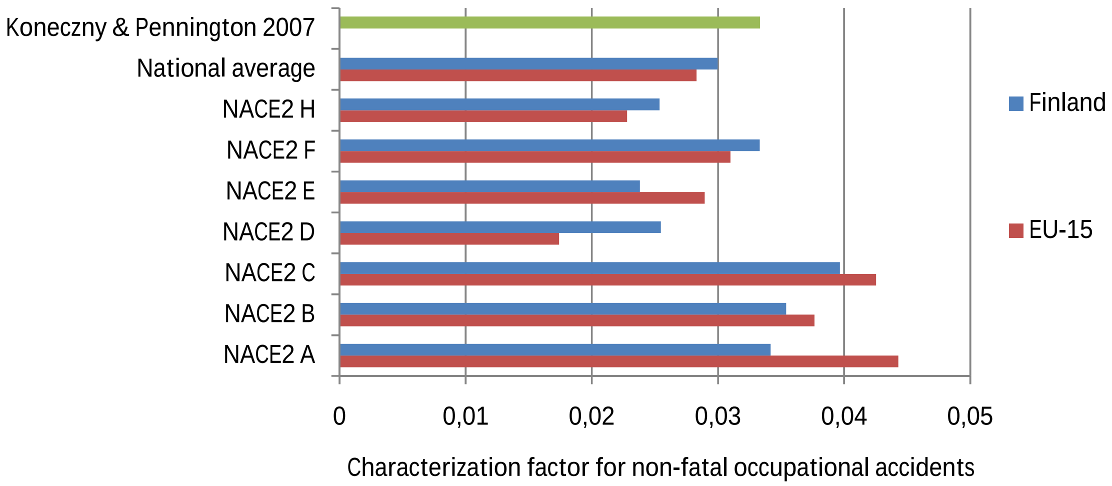

Figure4.3. *Characterization factors for non-fatal occupational accidents in selected industry sectors and the characterization factors reported by Koneczny and Pennington (2007, pp. 67)*

It should be noted that the actual healing time has in all cases been assumed as twice the time spent away from work. The assumption has been made based on an earlier study regarding USA. The difference between the actual healing time and time spent away from work is however likely to vary depending on the country due to for example different practices regarding substitutive work. The assumption can therefore make it that the characterization factors for different geographical areas are not equally valid. Further research on the difference between the time spent away from work and the actual healing time is needed in order to achieve more accurate characterization factors.

4.5.2.1.3 Characterization factors for commuting accidents in Finland

The characterization factors for commuting accidents have been calculated similarly as the characterization factors for occupational accidents. Industry specific characterization factors have not however been defined for commuting accidents as there is not enough detailed data available for that.

For **fatal commuting accidents** the characterization factor is taken as 39,3. The factor is calculated based on sex distribution reported by Statistics Finland for fatal commuting accidents and the age distribution reported by the Federation of accident insurance institutions (2011) for all commuting accidents as no age distribution for fatal commuting accidents alone is available.

The average durations of **non-fatal commuting accidents** have been calculated based on data regarding occupational accidents, as no detailed data for commuting accidents is available. Only the average life expectancy is calculated specifically for commuting accidents. The calculated durations are given in table 4.11 along with the shares of different medical conditions. More detailed data regarding the calculation of the durations is again presented in appendix A.

Table 4.11. *Average shares and durations for medical conditions resulting from non-fatal commuting accidents in Finland.*

Condition	**Share**	**Duration, calculated**	**Duration, this study**
Open wound	2,86%	0,13	0,13
Superficial injury	1,12%	0,13	0,13
Bone fractures	10,08%	0,73	0,73
Dislocation	3,04%	0,25	0,25
Sprains and strains	18,62%	0,26	0,26
Traumatic amputations (Loss of body parts)	0,02%	1,38	38,01[1]
Intracranial injury, incl. concussion	3,05%	0,26	0,26
Internal injury	7,74%	0,21	0,21
Burns, scalds and frostbites	0,05%	0,12	0,12
Poisonings and infections	0,02%	0,26	0,26
Drownings and asphyxiations	0,00%	0,03	0,03
Effects of sound, vibration and pressure	0,00%	0,09	0,09
Effects of temperature, light and radiation	0,00%	0,41	0,41
Shocks	0,05%	0,19	0,19
Multiple injuries	0,79%	0,91	0,91
Other not elsewhere mentioned	0,26%	0,38	0,38
Unspecified	0,67%	0,31	0,31
Unspecified, less than four days away from work	50,79%	N/A	0,02

[1] Life expectancy at the time of accident

Combining the data given in table 4.11 and the disability weights given in table 4.6 results in a characterization factor of 0,0240 for non-fatal commuting accidents. The value is notably lower than that for non-fatal occupational accidents. This is the result of two independent factors:

1. The shares of medical conditions with long durations and high disability weights are for many parts lower than for occupational accidents
2. The life expectancy at the time of commuting accidents is lower than the life expectancy at the time of occupational accidents

It should be noted that the characterization factor for commuting accidents is calculated largely based on data regarding occupational accidents, which carries with it a potential source of error.

4.5.2.2 Characterization factors for commuting accidents in EU-15 area

Calculating characterization factors for commuting accidents in EU-15 area is even more challenging than calculating them for Finland. Only little data is easily available regarding commuting accidents, and the data is in most cases very superficial.

In order to simplify the calculation of characterization factors, a number of assumptions have been made:

1. The same age and sex distribution is assumed for EU-15 as for Finland for both fatal and non-fatal commuting accidents

2. The same distribution of medical conditions resulting from commuting accidents is assumed for EU-15 as for Finland
3. The same durations of non-fatal accidents are assumed for commuting accidents in EU-15 area as for occupational accidents in the same area (apart from accidents leading to permanent disability, for which the duration is taken as the same as for fatal commuting accidents)

All of the assumptions listed above can have an adverse impact on the validity of the characterization factors. It is however assumed that the possible difference between the characterization factors calculated based on the above mentioned assumptions and the actual characterization factors is relatively small, and the error is therefore negligible compared to other potential errors.

Calculating the average life expectancy at the time of **fatal commuting accidents** using data from Finland results in characterization factor of 37,09. The characterization factors for **non-fatal commuting accidents** have been calculated based on shares and durations given in table 4.12 and the disability weights presented by Forbes and colleagues (2006). This results in characterization factor of 0,0186 for non-fatal commuting accidents.

Table 4.12. *Average shares and durations for medical conditions resulting from non-fatal commuting accidents in EU-15 area.*

Condition	**Share**	**Duration, calculated**	**Duration, this study**
Open wound	3,60 %	0,12	0,12
Superficial injury	1,46 %	0,13	0,13
Bone fractures	13,05 %	0,37	0,37
Dislocation	4,42 %	0,16	0,16
Sprains and strains	23,62 %	0,15	0,15
Traumatic amputations (Loss of body parts)	0,02 %	0,48	38,52[1]
Intracranial injury, incl. concussion	3,95 %	0,16	0,16
Internal injury	10,02 %	0,14	0,14
Burns, scalds and frostbites	0,06 %	0,12	0,12
Poisonings and infections	0,02 %	0,12	0,12
Drownings and asphyxiations	0,00 %	0,13	0,13
Effects of sound, vibration and pressure	0,00 %	0,10	0,10
Effects of temperature, light and radiation	0,00 %	0,11	0,11
Shocks	0,07 %	0,16	0,16
Multiple injuries	1,03 %	0,24	0,24
Other not elsewhere mentioned	0,33 %	0,16	0,16
Unspecified	0,87 %	0,16	0,16
Unspecified, less than four days away from work	35,65%	N/A	0,08

[1]Life expectancy at the time of accident

The characterization factor is lower than for Finland, which is due to the fact that the calculated average durations are shorter for EU-15 area than for Finland. This then again can be biased by underreporting or employees returning to work earlier than in Finland, but can also be the result of accidents being less severe on average.

4.5.3 Selection of right accident frequency and characterization factor

As discussed earlier, it is feasible to use the screening method as the first approach and resort to more accurate methods only if necessary. This means that the accidents should primarily be assessed using data that represents the average of the studied industry sector instead of trying to find more accurate data representing some specific processes. But what is the industry sector that should be chosen to represent the production of certain good, and what geographic region should the data represent? In case the production can be broken down to individual processes the selection of appropriate data should pose no difficulty. In most cases only aggregated data is however available, and it may be practically impossible to allocate the data to different processes.

The first approach could be to use data representing the sector of final production. However, according to Hofstetter and Norris (2003) in half of the United States industry sectors the supply chains account for almost 80% of the fatality cases and over 50% of the human health impacts of non-fatal injuries. This suggests that it is not feasible to just use the data representing the sector of final production, as the specific sector may have only a minor contribution to the overall impacts on human health. Instead, the sector with the highest contribution should be identified and data representing it used, or some average should be defined to represent all the sectors involved. This also makes it that it is in most cases not feasible to use data representing the geographical location of the final production, as a major share of the related processes can be expected to take place in other locations. **In the case study the first estimate could be to use data from the EU-15 area**, as it is taken as the reference area for the study. Data from a specific country should be used only if all of the relevant processes can be safely assumed to take place in the same country as the final production process.

The sectors that can be expected to account for most of the human health impacts can be qualitatively thinking limited to those discussed in the two preceding chapters. Also regional averages could be used to represent all involved industry sectors. The drawback of using regional averages is however that they are largely affected by a number of sectors that are not at all affecting the studied processes or are not included in the scope of the study. Therefore an average consisting of the NACE A-F and H sectors, which are the sectors that are included in the scope of this study, is defined using equation (13)[12].

$$N\dot{F}A_{average} = \frac{\sum WH_i * N\dot{F}A_i}{\sum WH_i} \tag{13}$$

[12] Here the equation for non-fatal accidents is given. The average accident frequency for fatal accidents is calculated similarly but using data for fatal accidents.

In equation (13) WH_i denotes the overall working time in the studied industry sector, $\dot{NFA}_i$ the respective accident frequency and $\dot{NFA}_{average}$ the average accident frequency. The working hours in different industry sectors have been calculated based on average working time in EU-15 area and amount of employees in different industry sectors as reported by Eurostat (2012i). Average of years 2008-2009 has been used for calculating the amount of employees as no data from 2005-2007 is available in appropriate form. Assigning the necessary values to equation (13) results in accident frequencies of 0,031 for fatal accidents and 39,4 for non-fatal accidents.

The best representative accident frequency is defined by comparing the data calculated based on the accident frequency for individual sectors and the two averages (EU-15 average for all sectors and EU-15 average for NACE A-F and H sectors) to the amount of accidents reported in GaBi for a number of different processes. The processes have been grouped into categories according to the service provided by them. The processes for the comparison have been handpicked from the processes that are in some way included in the case study. The comparison is carried out as a two step procedure:

1. **A qualitative study** of groups of processes to determine if some of them differ notably from the rest
2. **Two tailed one sample t-test** to determine if some of the accident frequencies discussed earlier can be used for background processes

Firstly the qualitative screening reveals that the number of fatal accidents reported for the manufacturing of ferrous metal products is notably greater than the value calculated using any accident frequency apart from that for mining sector (see appendix B). This observation is in line with the observations of Hofstetter and Norris (2003), who concluded that most of the fatal accidents occur in many cases in mining, forestry and agriculture. This makes it that the manufacturing of ferrous metal products has to be studied separately from the rest of the background processes. The positive side of this issue is however that an accident frequency for semi-finished steel products can easily be calculated based on the data given in GaBi databases. It is therefore feasible to eliminate the process group from further analysis, and to use the accident frequency calculated based on data given in GaBi for the manufacturing of any ferrous metal products. Other groups of processes do not differ strongly from one another, and they can therefore be all studied using a t-test for statistical analysis.

The t-test is carried out by comparing the values given in appendix B to the 100% value given in GaBi databases. The test will determine if some of the accident frequencies provide one with values sufficiently close to the ones given in GaBi databases. The t-test is considered suitable as the values calculated using different accident frequencies are reasonably well normally distributed (illustrated in figure 4.4. for NACE A-F and H average), and since the sample size is below 30. Null hypothesis is that the average of calculated values divided by the values given in GaBi is 1, i.e. that the calculated values are on average the same as those given in GaBi database. The α level of significance is taken as 0,05 meaning that with p-values below 0,05 the null hypothesis is rejected and the calculated values differ on average from those given in GaBi. Both the t- and p-values are given in appendix B for NACE A-F and H sectors, and two regional averages.

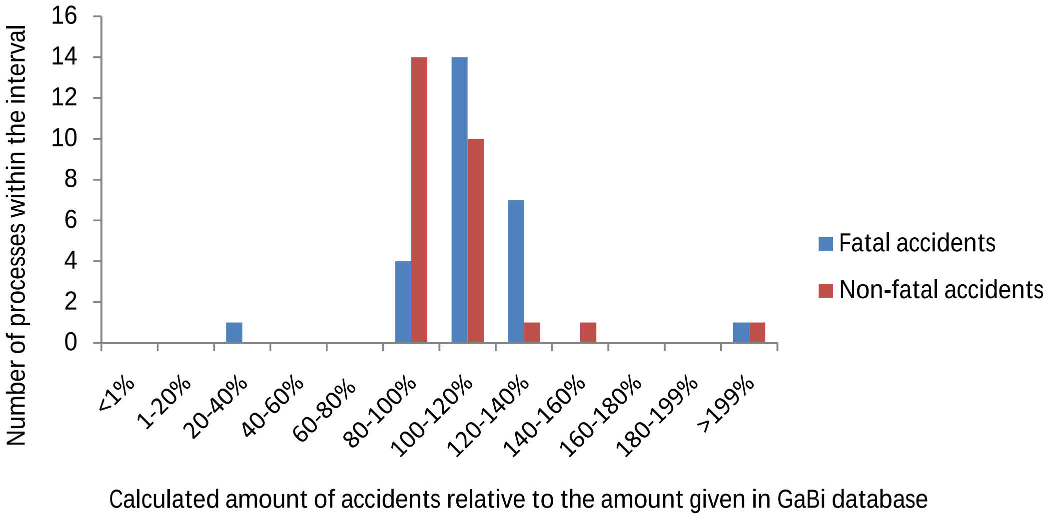

Figure 4.4. *Distribution of calculated amounts of fatal and non-fatal occupational accidents using average accident frequency for NACE A-F and H sectors, and the working time data given in GaBi databases relative to those given in GaBi databases for 27 different processes (all studied processes excluding the manufacturing of semi-finished steel products)*

Judging by the results given in appendix B, the average accident frequency of the NACE A-F and H sectors is the only one with p-value greater than 0,05 for both non-fatal and fatal accidents (0,22 for fatal and 0,17 for non-fatal accidents). Some sector specific accident frequencies seem to be statistically valid for studying either fatal or non-fatal accidents, but not both. **It is therefore recommended to use the average accident frequency of NACE A-F and H sectors for all background processes (apart from the manufacturing of ferrous metal products) for which only aggregated working time data is available.** For ferrous metal products the accident frequency calculated based on data available in GaBi should be used. A summary of the proposed reference accident frequencies is given in table 4.13.

Table 4.13. *Summary of accident frequencies that are proposed to be used for background processes for which only aggregated working time data is available*

Type of process	**Occupational accidents**		**Commuting accidents**	
	Fatal	Non-fatal	Fatal	Non-fatal
Manufacturing of semi-finished steel products, European average	0,134	25,4	0,0095[1]	4,8[1]
Other processes, EU-15 average	0,031	39,4	0,0095[1]	4,8[1]

[1] EU-15 average as no more detailed data is available

Besides those values given in table 4.13 also values for a specific country can be used in case all of the processes take place in the same country. The values for a specific country can be calculated using equation (4) given earlier in chapter 4.4.3.3. But as stated earlier, **country specific values should be used only if all of the relevant processes can be safely assumed to take place in the specific country**.

The characterization factor for the average of NACE A-F and H sectors is calculated similarly as the accident frequency. Replacing the accident frequency of the specific industry sector with the respective characterization factor and assigning this along with the working time data in equation (13) results in characterization factor of 33,09 for fatal and 0,0353 for non fatal occupational accidents. For commuting accidents the accident frequencies are taken as those reported for the EU-15 area, and for the accidents related to the manufacturing of semi-finished steel products as those calculated for the average of NACE A-F and H sectors as no more detailed data is available. **The average characterization factors should be used in all cases where also the average accident frequency is used.**

Finally, it should be noted that the recommendations given here apply only for the case study or other studies with similar scopes. These recommendations cannot be applied to studies dealing with notably different product systems.

4.6 Limitations of the proposed method and reference data

4.6.1 Applicability of the method for different purposes

LCA studies can be grouped into three categories based on their intended decision support orientation, and the changes in the background processes resulting from changes in foreground processes: studies with micro-level decision support, studies with meso/macro-level decision support, and accounting studies. Meso/macro level decision making means that changes in the foreground system can result in notable changes in the background systems, while micro level decision making means that no notable changes in the background processes occur. Each type of study has specific requirements regarding the data quality, inventory analysis and in some cases even impact assessment. The division is presented in figure 4.5. (European Commission 2010a; European Commission 2010d)

		Extent of process-changes in background system or other systems	
		None / small scale	Large scale
Decision support	Yes	Micro-level decision support	Meso/macro-level decision support
	No	Accounting	

Figure 4.5. *Division of different types of LCA studies based on their support for decision making (European Commission 2010d, pp. 10-12)*

Studies that are aimed at supporting decision making at meso/macro-level should be modeled so that the long-term changes in relevant background processes are taken into account (European Commission 2010d, pp. 10-12). In the case of waste gasification for example, background-processes that can be significantly affected by foreground processes include e.g. transportation, landfilling and energy production processes. The method used for the inventory of accidents however fails to consider any long-term changes in the background processes. This method is therefore not applicable for studying extensive changes in the studied system, but is rather limited to accounting and micro-level decision support. In case meso/macro-level decision support is needed, the inventory should be based more on case specific results of risk assessments that consider the long-term changes in the risk profiles of each relevant process.

4.6.2 Data quality of inventory data

The data quality of inventory data used for LCA studies can be determined based on six data quality indicators (European Commission 2010d, appendix B):

1. Technological representativeness (TeR)
2. Geographical representativeness (GR)
3. Time-related representativeness (TiR)
4. Completeness (C)
5. Precision / uncertainty (P)
6. Methodological appropriateness and consistency (M)

Each aspect can be given a score from 1 (best) to five (worst) based on criteria presented by European Commission (2010d, appendix B) For inapplicable data quality indicators the score is taken as zero. The overall data quality can then be determined using equation (14), where DQR is the data quality rating of the specific dataset; i the number of applicable data quality indicators; TeR, GR, TiR, C, P and M the values of data quality indicators; and X_w the weakest quality level.

$$DQR = \frac{TeR+GR+TiR+C+P+M+X_w*4}{i+4} \qquad (14)$$

With DQR of 1,6 or smaller, the data set is of high quality. With DQR of 16-3,0 the overall quality rating is “basic quality”, and with DQR of over three but not more than four the overall quality rating is “data estimate”. For the data to be useful, its quality level has to be practically at least “data estimate”. (European Commission 2010d, pp. 61)

Although the data quality indicators are meant to be used primarily with LCI datasets, they are to great extent applicable for the inventory method as well. When using the indicator for the proposed method, the data quality scores are given according to the best data quality level that can be achieved using the proposed method. The scores of each data quality indicators are given in table 4.14. The scores are determined qualitatively, taking into consideration the existence and limitations of literature data, applicability of case specific data and methodological limitations. The mere possibility to use case specific data is not considered sufficient to achieve best possible score, as it may in many cases be practically impossible to obtain. Also, case specific data is often based on very small sample sizes, which makes it hard to use it for statistically valid analysis.

Applying the scores given in table 4.14 to equation (14) results in overall data quality rating of 2,4. In other words, data quality level of “basic quality” can be achieved at best using the proposed method. The data quality will however most likely fall under the category of “data estimate” in most case studies given that best applicable data quality cannot often be achieved.

The overall data quality is foremost affected by the poor precision of data and geographical representativeness. Good precision is practically impossible to achieve without increasing the uncertainties: if average data with large sample size is used, the uncertainty is somewhat small. However, the precision can be very poor given that the variation within the sample may be great. On the other hand, using case specific data with small sample size can improve precision but only at the cost of increased uncertainty resulting from too small sample size.

The relatively low overall data quality score suggests that **the method is best used together with more accurate tools**. LCA is not in general a stand-alone tool. However, given that the method can achieve at best sufficient data quality, it is still better than achieving no data at all.

Table 4.14. *Best levels of data quality that can be achieved (practically thinking) using the proposed method for assessing occupational safety within LCA framework*

Data quality indicator	Score	Description
Technological representativeness (TeR)	1,5	- Small technological differences (e.g. the use of different safety devices) can have notable impact on the results. The applied technology is only rarely known to the extent that also the existence (and impacts) of different safety devices would be known. + Different technologies can be covered at upper level (e.g. road vs. rail transportations). + The machinery used in e.g. EU should meet common minimum safety standards, and the average values should therefore represent at least technology meeting the minimum standards. + Case specific data can be used, if available; the applicability of case-specific data is however limited because of small sample sizes.
Geographical representativeness (GR)	2	- Statistics are mainly available for developed countries only. Estimates or calculated values have to be used for developing countries. - Local conditions can affect for instance the amount of accidents associated with transportations, which makes it that national averages may not be sufficiently accurate for some parts. + Estimates presented in literature can be used to fill in data gaps (e.g. Hämäläinen et al. 2005). + The use of case specific accident frequencies and working times is possible given that the data is available; the applicability of case-specific data is however limited because of small sample sizes.
Time-related representativeness (TiR)	2	- Only historical data is available. + Data that reflects the current situation is for most parts available. + Future situation can be estimated based on current long-term trends.
Completeness (C)	1,5	+ Theoretically, all relevant processes can be covered (at least at some level of precision). However, estimating the relevance of processes considering the overall impacts can be hard as only limited literature data exists. As a result, ensuring that all relevant processes are considered may be very time and resource consuming task.
Precision / uncertainty (P)	3	- Both accident frequencies and working times associated with the process can vary significantly between different companies. As a result, notable variation in the calculated amounts of accidents can occur. - Severe accidents occurring only rarely can have notable impact on the results, but can only hardly be accurately inventoried. + Based on the results given in appendix B and in chapter 4.5.3, the proposed method provides one in most cases with values close to industry averages. + Case specific data can be used, if available; the applicability of case-specific data is however limited because of small sample sizes.
Methodological appropriateness and consistency (M)	1	+ Methodology established by PE international and European Commission is used in all cases.

4.6.3 Applicability of the impact assessment method

According to ISO 14044, impact assessment methods have to be in line with the following requirements:

1. They are internationally accepted
2. They should represent the aggregated impacts of elementary flows of the product system on the category endpoint(s)
3. Value choices and assumptions should be minimized during the selection of impact categories, category indicators and characterization models
4. Double counting should be avoided (unless required by the goal and scope definition)
5. The characterization models should be scientifically and technically valid, and based upon a distinct identifiable environmental mechanism
6. The extent to which characterization factors are valid is to be identified
7. The category indicators should be environmentally relevant

The concept of disability adjusted life years, which is proposed to be used, is a concept established by World Health organization. It is applicable for both diseases and injuries, and is promoted to be used for studying impacts on human health in LCA. It also combines both fatal and non-fatal injuries and illnesses under a single numerical score. With these aspects considered, the proposed impact assessment method is in line with the first, second, third and fifth requirement given above.

The proposed impact assessment method is also in line with the fourth requirement, as occupational accidents and commuting accidents only affect a single one area of protection and category endpoint. No double counting should exist within the impact category either, assuming that the data used for calculating the characterization factors is valid.

The sixth and seventh requirement is partially answered by the case study. It is known that accidents can have notable impact on human health (Hofstetter & Norris 2006), and that the DALY values are generally specific to a given geographical are only (European Commission 2010d). However, the question if they are relevant from the perspective of the intended application of this method can only be answered through a case study. The case study will also provide some additional information for identifying, if there are additional boundaries besides the geographical ones limiting the validity of the characterization factors. The characterization factors calculated for a number of Finnish industry sectors hint that the use of average characterization factors might not be feasible even for a single geographical area, but this observation has to be confirmed through the case study.

A further aspect that has to be considered besides the requirements listed earlier, is the accuracy of characterization factors. The proposed characterization factors are calculated based on partially missing data, which is completed with estimated or calculated secondary data. Also the number of accidents, based on which the characterization factors have been calculated, is in some cases small. Furthermore, the characterization factors are actually determined mainly by accidents leading to amputations: 32-63% of the overall value of characterization factor for non-fatal accidents in different Finnish industry sectors results from accidents leading to amputations. Even small changes in the amount of such accidents can therefore make it that the characterization factors calculated here are obsolete. For example, if in mining and quarrying industry the amount of accidents causing amputation is increased from one accident in 2008 (which is in fact a calculated value) to two accidents with the amounts of other types of accidents remaining constant, the characterization factor is increased by 49%.

Another factor increasing the uncertainty of the characterization factors is that there are some slight inconsistencies in the data used for calculating them. While the inventory data is as a rule calculated for years 2005-2009, the characterization factors have for most parts been calculated only for year 2008 as no data is available for the other years. As an exception to rule, the characterization factors for fatal accidents have been calculated based on average data for years 2005-2009. As a result, the sample sizes are partially quite small and there are slight inconsistencies in the method for calculating the characterization factors.

The sensitivity of characterization factors actually makes it that 100% or even greater variation between the “actual” characterization factors and those calculated for the proposed method are anything but impossible. The variation is still smaller than what can be expected for some LCI results, and the characterization factors should not therefore be considered completely inapplicable. Instead, the uncertainty again highlights the fact that LCA – and especially the study of occupational accidents within the LCA framework – tells only the story of potential impacts. This variation has to also be kept in mind while interpreting the results.

5 Case study of a waste gasification plant

This chapter provides one with the results of the case study section's inventory analysis and impact assessment (i.e. the LCI and LCIA stages of LCA). The inventory assessment results will be discussed in detail to support any later studies and to ensure that the reporting requirements of ISO 14040 and 14044 are met. The impact assessment results will be discussed only briefly. They will be discussed in greater detail in chapter 6 (Interpretation of the case study results).

5.1 Life cycle inventory analysis

The inventory analysis is carried out in two parts as discussed in previous chapter:

- Inventory of foreground processes (based on case specific data)
- Inventory of background processes (based on calculated average data or data from literature)

In addition, the inventory is divided into the inventory of input and output data, and the inventory of occupational accidents and accidents related to commuting. Input and output data is used to determine the associated processes, and if the data covers elementary flows, also environmental impacts. The calculation procedures, data sources and assumptions regarding the collection of inventory data have been discussed in this chapter. The calculation procedures and assumptions regarding data taken directly from LCI databases have as a rule not been given here, but it has been referred to.

The inventory data itself is given in this only at the level of inputs and outputs to specific processes. Aggregated data regarding elementary flows to and from the studied system is not provided here. Inventory data regarding occupational accidents and commuting accidents, which are regarded as elementary flows, will also not be given here but in appendix C.

The data given in this chapter and in appendix C is marked according to the inventory method. The markings have been made primarily to ease the data quality analysis. Different markings and their meanings are given in table 5.1.

Table 5.1. *Abbreviations used for indicating different inventory methods*

Abbreviation	**Description**
PC	Primary calculated: data that has been calculated based on primary (case specific) data
SC	Secondary calculated: data that has been calculated based on secondary data
L	Literature, data taken from literature or LCI databases
A	Assumption, data based on own assumptions

5.1.1 Foreground processes

5.1.1.1 Construction of the gasification plant

5.1.1.1.1 Input and output data

The gasification plant consists mainly of different kinds of steel products. Also concrete, insulating materials, some ceramic materials, glass and plastics have been used for the gasification plant. The foundation is built of reinforced concrete.

The amounts of different **materials used for the buildings and equipment** have been calculated by Metso Power's personnel for the specific case. The foundations and road infrastructure etc. are beyond the scope of Metso Power's delivery, and there is therefore no case specific data available regarding the amounts of materials used for them. The amounts of materials used for the foundations and roads have therefore been estimated based on data reported in literature. It should be noted that there is great variation in the literature data as the consumption of materials depends on a variety of different factors and the values used for the study are at best a sophisticated estimate (Dones et al. 2007, pp. 99-100). The materials used for the gasification plant are given in table 5.2.

The production of different materials has been modeled based on data reported in GaBi and ecoinvent databases for best representative products. The best representative processes have been given in table 5.2 for the raw materials needed for the power plant. The standard transportation distances reported by Frischknecht and colleagues (2007, pp. 12-14) have been used for all materials apart from ceramic materials and power plant equipment. Half of the ceramics are known to be transported to the construction site from northern UK by ship while the rest are transported to the site from western Sweden. For the ceramic materials an average transportation distance of 1620 km by ship and 200km by truck is therefore used. For power plant equipment the transportation distance is taken as 150km.

Table 5.2. *Construction materials used for the gasification plant*

Material	Mass [t]	Best representative process and source of data
Steel, buildings and equipments	7636 (PC)	Power plant component, Metso Power Tampere workshop (internal data)
Steel, concrete reinforcements	1500 (A)[1]	Steel rebar (Worldsteel)
Brickwork and concrete, buildings and equipments	250 (PC)	Concrete, normal (ecoinvent)
Concrete, foundations	30000 (A)[1]	Concrete, normal (ecoinvent)
Insulations	353 (PC)	Rock wool, 30-180kg/m³ (GaBi)
Glass, windows	10 (A / PC)	Uncoated flat glass (ecoinvent)
Ceramic materials, equipment	44 (PC)	Calcium silicate (GaBi)
Plastics, buildings and underground structures	75 (A / PC)	Polyethylene granulate
Bitumen	200 (A)[2]	Bitumen (GaBi)

[1]Estimate based on Dones et al. (2007, pp. 100), Doka (2003, pp. 49) and Spath et al. (1999, pp. 24)
[2]A rough estimate based on Doka (2003, pp. 49) and Bauer (2008 pp. 25-31)

The further **processing of materials** has been considered only for the steel parts. The steel parts are assumed to be pre-manufactured to different kinds of elements or power plant equipments. The pre-manufacturing is approximated in all cases based on data regarding the operations taking place in Metso Power’s Tampere workshop. In reality only a small part of all equipment is manufactured by Metso Power in the Tampere workshop. In this case it has not been considered useful or relevant to collect more detailed data from suppliers. Therefore, the data considering the manufacturing of equipment and other steel structures represents a very rough estimate. The direct emissions to air from the pre-manufacturing processes have been calculated based on material inputs and emission factors reported in literature for a variety of processes. The emissions from welding have been calculated based on data reported by Classen and colleagues (2009, pp. 845-858) and U.S. Environmental protection agency (2008). The emissions from painting have been inventoried based on Metso’s internal data, and the emissions from the use of light fuel oil and diesel based on data reported by Jungbluth (2007, pp. 199-218) for light fuel oil and Kellenberger and colleagues (2007, pp. 553-559) for diesel. Summary of direct emissions from the workshop is given in appendix D along with the rest of the inventory data regarding the pre-manufacturing stage[13]. The transportation distances for different materials have been taken as the standard distances reported by Frischknecht and colleagues (2007, pp. 12-14).

The **construction of power plant infrastructure** requires the use of energy in building machines and site offices. Also waste is formed during the construction process due to for example excavation. All of the waste is in this case assumed to be recycled or reused. Steel waste is assumed to be recycled as material, packaging waste incinerated and excavated ground reused at some other construction site. The waste formation associated with the

[13] Appendix D is available for Metso Power’s and Metso Corporation’s internal use only, and will not be published as a part of the public version of this document.

construction of power plant infrastructure has been estimated based on Metso Power's internal data and data reported in literature. The energy consumption associated with the construction of the power plant is estimated based on values reported in literature for hard coal power plants as no data is available specifically for waste incineration let alone gasification plants. Data regarding energy consumption and waste formation is summarized in table 5.3.

Table 5.3. *Energy needed for the construction of power plant infrastructure, and an estimate of the waste produced during the construction processes*

Input / output	**Amount**	**Reference**
Diesel	14000 MWh (SC)	Calculated based on Dones et al. (2007) assuming standard amount of energy use in relation to the mass of the power plant
Electricity	3300 MWh (SC)	Calculated based on Dones et al. (2007) assuming standard amount of energy use in relation to the mass of the power plant
Thermal energy	14000 MWh (SC)	Calculated based on Dones et al. (2007) assuming standard amount of energy use in relation to the mass of the power plant
Excavated soil	34000 t	Volume of excavated ground estimated as the same as the volume of concrete used for foundations. Density of excavated ground estimated as 2,7t/m3 based on Ronkainen (2012)
Packaging waste: steel	Based on internal unpublished data (A)	Estimated based on the use of packaging materials in Metso Power's workshops
Packaging waste: wood	Based on internal unpublished data (A)	Estimated based on the use of packaging materials in Metso Power's workshops

The excavated soil is assumed to be used as landfilling material, and no burden is considered for its disposal. The other waste formed during the construction processes is modeled using the generic waste disposal processes discussed later in chapter 5.1.2.4.

In addition to waste, the construction activities account also for some emissions. These have as a rule been inventoried as a part of the respective input data (e.g. emissions from the use of diesel in building machines have been inventoried using the respective ecoinvent data set). A notable exception to the rule is formed by particulate emissions, which arise to a high degree directly from the land excavation, blasting, earth moving and other construction processes (Spath et al. 1999, pp. 24). According to Spath et al. (1999, pp. 24) the construction activities account for the formation of some 2,6 tons of particulate matter per hectare and month of activity, and according to United States Environmental Protection Agency (1995) some 2,7 tons per hectare and month of activity. The emission factors are however applicable to a certain type of soil and climate only and can be used to estimate the emissions only from certain stages of the construction process (United States Environmental Protection Agency 1995). Here it has been assumed that the construction operations causing heavy dusting take place during six months and at an area of two hectares. Both are pure assumptions, and in case dusting seems to be notable contributor to the overall results, these values have to be revised.

5.1.1.1.2 Occupational accidents and commuting accidents

The amounts of occupational accidents related to the production of materials have been inventoried based on data given in GaBi database or best representative data available in literature as discussed in chapter 5.1.2.3. The accidents directly associated with the pre-manufacturing of steel parts and equipment are inventoried based on Metso Power's internal data regarding average working time relative to the average production, and average accident frequency at selected production sites. The amount of accidents associated with the pre-manufacturing of power plant equipment is given in appendix C (table C1). The amount of indirectly associated accidents has been calculated based on data available in GaBi databases and literature for the energy and material production, and waste disposal processes as discussed in chapters 5.1.2.2, 5.1.2.3 and 5.1.2.4.

The amounts of accidents associated with the construction activities have been calculated partially based on Metso Power's internal data and partially based on literature data. For this study only publicly available data regarding the working time associated with the construction activities has been used to ensure the confidentiality of any internal data. The working time associated with the construction of the studied plant is estimated as ca. 108000 man-hours in the plant's environmental impact assessment (Lahti Energia 2005). The working time is however probably underestimated, or at least not suitable for other cases, as the working time associated with the construction of some other waste incineration plants have been estimated to be notably greater. For this study an average value is therefore used. The average is calculated by multiplying the average amount of working hours per one MW of fuel power with the fuel power of the studied plant. The average is calculated based on a variety of references given in literature for Finnish waste incineration and other power plants. The references are summarized in figure 5.1.

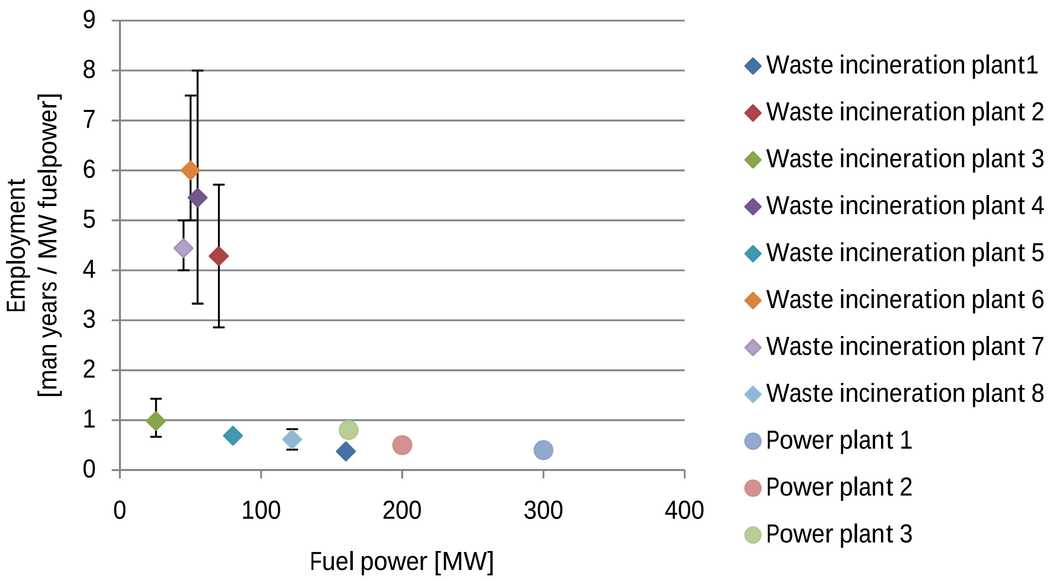

Figure 5.1. *Working time associated with the construction of power plants. Limits of error represent the smallest and greatest estimate given in literature for the specific plant (if available). (Lahti Energia 2005; Oulun Energia 2004; Seinäjoen Energia Oy 2004; Porin Lämpövoima Oy 2004; Vapo Oy 2006; Etelä-Karjalan Jätehuolto Oy 2011; Westenergy Oy Ab 2008; Vantaan Energia Oy 2007; Laanilan Voima Oy 2009; Myllylä 2012; Tanninen 2008)*

As can be noted from the figure, the working time associated with the construction of waste incineration plants 2, 4, 6 and 7 is notably greater than what is estimated for the rest of the cases. This can be the result of overestimating the employment during construction, but it can also indicate that the construction processes take place in areas, where for example a lot of earth moving is needed. Also, it can be expected that the working time associated with the construction of the gasification plant is slightly higher than on average as the studied plant is first of its kind, and the construction process can be therefore faced with unexpected delays. Therefore, the four exceptionally high values have not been excluded from the calculation when determining the average working time. Calculating the average value based on references given in figure 5.1 results in 2,23 man-years of work per one MW of fuel power. For the studied power plant this means the overall working time of ca. 350 man years (i.e. 630000 working hours). The average excluding the four waste incineration plants with notably higher employment than the rest of the cases is 0,623 man years per MW of fuel power, indicating that the value used for this study is probably overestimated.

Metso Power's and its subcontractors' share of the total working time is taken as 50%[14]. The rest is taken as working time of other contractors working in the site for other companies than Metso. The accident frequencies for Metso Power's and its subcontractors' employees are taken as those reported for Metso Power's capital construction sites in 2010-2011. For the rest of the work, the average accident frequencies in Finnish construction sector have been used. The amounts of accidents for Metso's, its subcontractors and other contractors' employees are given in appendix C (table C1).

The accidents associated with the production of energy needed during the construction have been inventoried based on data given in GaBi for different energy production methods and waste disposal activities. These processes are discussed in detail in chapters 5.1.2.2 and 5.1.2.4.

5.1.1.2 Operation of the gasification plant

5.1.1.2.1 Input and output data

The gasification plant is expected to be operational for at least 25 years, during which time it is expected to use some 6,25 Mio tons REF. The fuel is converted in to electricity and heat with ca. 88% total conversion efficiency. 1 ton of REF will generate some 1,4 MWh electricity and 2,5 MWh utilizable heat. The values represent situation where the plant is operated according to its design parameters. The design values will be used for all inputs and outputs associated with the plant's operation.

Most of the materials being fed to the gasification plant consist of the gasified REF. In addition, a number of chemicals and additives are needed for the flue gas cleaning. The amount of chemicals and additives consumed at the plant is inventoried based on internal data and data reported in the environmental permit. The material inputs that have been considered in this study are given in table 5.4. Standard distances reported by Frischknecht and colleagues (2007, pp. 12-14) have been assumed for the transportation of the materials. For some materials listed as "other materials" in table 5.4 case specific transportation distances and modes of transportation have been used.

Table 5.4. *Material inputs to the gasification plant (Hämeen Ympäristökeskus 2005)*

Input	**Amount [kg / t waste]**
Sand	23,1
Calcium carbonate	23,1
Calcium hydroxide	7,92
Activated carbon	0,556
Other materials	Based on internal, unpublished data

[14] 50% is a rough estimate. The actual working time of Metso Power's and its subcontractors' employees is not published data, and will not therefore be used for this study.

Most of the materials that have entered the gasification plant leave it as atmospheric releases. The emissions to air include a wide variety of different gaseous compounds and particulate matter. **In this study only carbon dioxide and the emission components that are regulated by European legislation have been taken into account.**

The upper limit for a variety of emissions to air is set in the European legislation, and this is used also for this study as the upper limit value. In reality the emissions are most likely smaller than they could legally be. The use of maximum allowed emissions for the study is in line with the common practice of using conservative data to ensure that no overly optimistic assumptions are done. However, it makes it that the environmental impacts on human health are overestimated compared to those caused by occupational accidents, which can ultimately lead to biased conclusions. It is therefore necessary to also consider the more optimistic cases regarding airborne emissions and their impacts on human health.

In order to ensure that no over or underestimation of emissions takes place, both an upper and lower limit has been determined for the emissions to air. The upper limit, which is also the reference case for this study, is calculated based on the legal limit set in the European directive 2000/76/EC and internal data regarding flue gas formation. The lower limit is set as the lowest technically feasible limit, which is calculated based on the lowest emission limit as set in the European Best Available Techniques (BAT) reference document (BREF). Both the upper and lower limit emissions to air are given in table 5.5.

The emissions of carbon dioxide have been inventoried based on the amount of fossil CO_2 emissions estimated in the Environmental impact assessment of the gasification plant. This estimate is done based on the default emission factor for recycled fuels as suggested by Statistics Finland (2012a). In reality the CO_2 emissions can be expected to be slightly lower, as the average share of biogenic material in waste is 60%, while in the studied case the share of biogenic waste is assumed to be 60-80% (Lahti Energia 2004; Statistics Finland 2012a).

***Table** 5.5. Upper and lower limit values for emissions to air*

Emission component	**Upper limit value [kg / t waste]**	**Lower limit value [kg / t waste]**
CO_2	636[1]	636[1]
CO	0,452[2]	0,0452[3]
TOC	0,0904[2]	0,00904[3]
NOx	1,81[2]	0,362[3]
SO_2	0,452[2]	0,00904[3]
Dust	0,0904[2]	0,00904[3]
HCl	0,0904[2]	0,00904[3]
HF	0,00904[2]	0,00452[4]
Dioxins and furans (as TEQ)	9,04E-9[2]	9,04E-10[3]
Cd + Tl	4,52E-4[2]	4,52E-5[3]
Hg	4,52E-4[2]	9,04E-6[3]
Sb+As+Pb+Cr+Co+Cu+Mn+Ni+V	0,00452[2]	4,52E-5[3]

[1] Hämeen Ympäristökeskus 2005; Statistics Finland 2012a
[2] Directive 2000/76/EC; internal data regarding flue gas formation
[3] Lowest value given in European Commission (2006, pp. 440-441); internal data regarding flue gas formation
[4] 50% of the upper limit value

The incineration of product gas formed in the gasification process produces also some solid residues (referred to as incineration residues), that are either too heavy to be carried along with the flue gas or that are separated from the flue gas in order to purify it. In the studied case three different types of residues are collected from the process: bottom ash, fly ash and air pollution control (APC) residues. Residues consist of various different chemical elements and compounds. The amounts of different residues formed during the gasification of one ton REF are calculated based on internal unpublished data, and data reported by Hämeen Ympäristökeskus (2005) and Lahti Energia (2004; 2005).

Residues from the gasification and incineration contain for example heavy metals and different flue gas cleaning reaction products. The composition of residues is modeled based on Metso Power’s internal calculated data and will not be published as a part of this thesis. In general the composition of incineration residues can be considered to be roughly similar to the composition of ashes reported by for example Kaartinen and colleagues (2007). The inputs and outputs associated with the disposal of residues have been discussed later in chapter 5.1.1.3.

5.1.1.2.2 Occupational accidents and commuting accidents

The occupational accidents related to the operation of the power plant have been inventoried taking into account only the normal operation of the plant. The accidents related to the maintenance, renewals and possible future upgrades have not been considered here. This has been done as the accidents occurring during maintenance work are mainly complied in the accident statistics as a part of the NACE2 D sector activities and are therefore already covered when by the study. Inventorying them also separately would therefore lead to double counting of the accidents.

The studied gasification plant is estimated to deliver jobs to six people. The amount is probably lower than on average, as the plant is located next to an existing power plant and can therefore be partially operated by the employees of the existing plant. Indeed, it can be observed that the employment estimated for the studied plant is notably lower than on average when comparing it to the employment estimated for a number of other waste incineration plants and other power plants (figures 5.2 and 5.3). Although there are some differences in the types of fuel used in the reference plants, they should not affect the working time associated with their operation (Halonen et al. 2003, pp. 13-14). Instead, the working time is foremost affected by the capacity of the plant and its annual operating time.

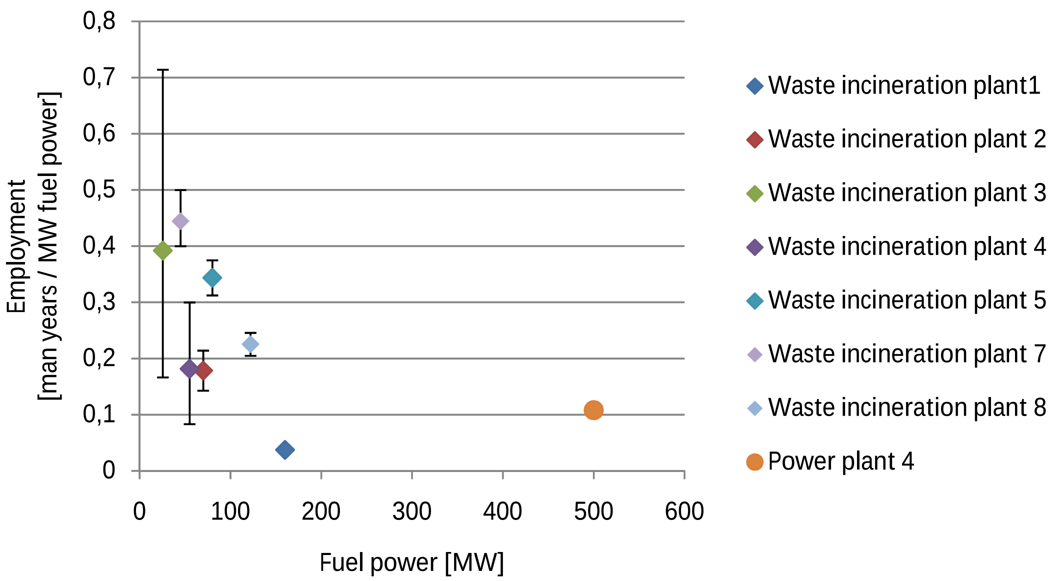

Figure 5.2. *Working time associated with the operation of power plants relative to the fuel capacity of the plant. Limits of error represent the smallest and greatest estimate given in literature for the specific plant (if available). The same power plants have been used as reference as in figure 5.2 in case data regarding them is available. (Lahti Energia 2005; Oulun Energia 2004; Seinäjoen Energia Oy 2004; Porin Lämpövoima Oy 2004; Vapo Oy 2006; Westenergy Oy Ab 2008; Vantaan Energia Oy 2007)*

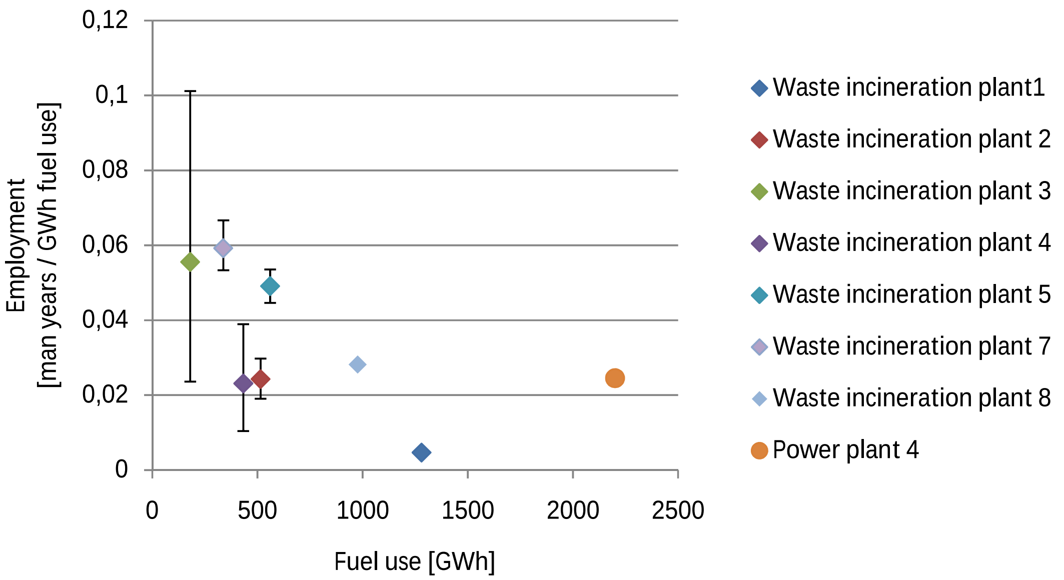

Figure 5.3. *Working time associated with the operation of power plants relative to the fuel use. Limits of error represent the smallest and greatest estimate given in literature for the specific plant (if available). The same power plants have been used as reference as in figure 5.2 in case data regarding them is available. (Lahti Energia 2005; Oulun Energia 2004; Seinäjoen Energia Oy 2004; Porin Lämpövoima Oy 2004; Vapo Oy 2006; Westenergy Oy Ab 2008; Vantaan Energia Oy 2007)*

The average working time of the reference plants illustrated in figures 5.2 and 5.3 is 0,239 man years per MW of fuel capacity, which corresponds to 0,0336 man years per one GWh of fuel use. However, the average working time relative to the fuel use of fuel capacity is not constant, but decreases while the capacity and also annual usage of fuel increases (Halonen et al. 2003, pp. 13-14). Given the small sample size of reference plants it is not possible to determine causality between the fuel use and the employment in the power plants. The unweighted average has therefore been used for this study even though it can lead to an overestimation of the actual working time. In order to calculate the working time relative to the gasification of one ton REF, it has to be divided by the energy content of waste (16,1 MJ/kg).

The amounts of accidents related to the normal operation of the plant can then be calculated based on the working time and accident frequency for NACE2 D. Case specific accident frequency cannot be used, as the plant is operated over the next twenty years time and there is therefore no statistical data available at the moment. Here the accident frequency for energy industries is used, as the studied plant is considered foremost a power plant. The amounts of accidents relative to the amount of gasified REF are listed in table C2 in appendix C.

The accidents related to the production of materials used at the power plant have been inventoried as described in chapter 5.1.2.3. The accidents related to the transportation of materials have been inventoried based on distances discussed in earlier chapters and generic transportation processes.

5.1.1.3 Disposal of incineration residues

5.1.1.3.1 Input and output data

Incineration residues can either be disposed in landfills or other waste deposits, or recycled for use as materials (Hämeen Ympäristökeskus 2005). The applied technique for the treatment of residues is foremost determined by their properties. In general the recycling of incineration residues is the environmentally most preferable solution, but it can be hindered by the properties of the residues. Therefore in order to follow the precautionary principle, the ashes are assumed to be disposed rather than recycled.

Also the disposal of ashes in landfills may not be possible without further treatment of ashes (Kaartinen et al. 2007). For this study it has been assumed that bottom ash can be landfilled as such and is disposed in a slag compartment of sanitary material landfill. Fly ash and APC residue then again are assumed to be processed prior to their disposal in order to meet the quality criteria for landfilled waste. In general there are a lot of different processing methods that may or may not be applicable depending on the properties of ashes (Kaartinen et al. 2007). For this study stabilization with cement is assumed followed by disposal in residual material landfill as suggested by Doka (2003, pp. 32). The assumption represents one possible scenario for the treatment of ashes, but is not necessarily the one used in the reference case.

The disposal of ashes requires the use of energy as well as the construction of necessary infrastructure. These have been inventoried based on the data reported by Doka (2009a). The outputs from the landfill consist of emissions to air and ground water. The emissions to air take place over a relatively short period of time due to the use of fossil fuels during the processing of waste. They have been inventoried based on data given for the respective processes in ecoinvent and GaBi databases.

The emissions to water take place due to the dissolving of material to landfill leachate. The dissolving takes place over a long period of time, and the emissions have to be therefore estimated based on chemical and physical properties of different chemical elements. In this study the transfer coefficients reported by Doka (2009a, pp. 68-69, 72-73) have been used for calculating the emissions from landfills. The emissions have been reported for two time frames: short period time frame (0-100 years) and an infinite time frame based on internal data regarding the composition of different residues.

The ashes are assumed to be transported to the landfill by trucks. For bottom ash the transportation distance is taken as 10 km, and for fly ash and APC residues as 50 km as suggested by Frischknecht and colleagues (2007, pp. 12-14).

5.1.1.3.2 Occupational accidents and commuting accidents

The amounts of occupational and commuting accidents related to the disposal of ashes have been inventoried based on generic landfilling process described in chapter 5.1.2.4. When calculating the accidents, the weight of stabilization materials and the resulting increase in working time per kilogram on incineration residues has been taken into account[15]. The accidents related to the production of cement used for the stabilization of the ashes have been inventoried based on the data discussed in chapter 5.1.2.3.

The occupational and commuting accidents associated with the transportation of incineration residues from the gasification plant to the landfill have been inventoried based on the average transportation processes. Standard transportation distances described by Frischknecht and colleagues (2007, pp. 12-14) have been assumed for the transportations.

5.1.1.4 Deconstruction of the gasification plant

The deconstruction of power plants is a rather poorly documented aspect of energy generation systems. Most of the end-of-life models of waste incineration and power plants include only the environmental impacts arising from the disposal and recycling of construction materials. The inputs and outputs related to for example the operation of the machinery used for the deconstruction activities have been in most cases completely omitted as they are assumed to be insignificant regarding the overall environmental impacts.

When it comes to occupational safety such assumption cannot be made as there is practically no information available to support the idea that deconstruction activities would be insignificant regarding the overall impacts. It is therefore necessary to evaluate also them as a part of this study. To ensure consistency between the environmental health impacts and the occupational health impacts, these processes have to be studied from the environmental perspective also.

Obtaining case specific data regarding the deconstruction activities is practically impossible as the activities are expected to take place some twenty years in the future. Secondary data has to be therefore used. Also this is quite problematic as very little data exists in literature. In fact, the only publicly available documents concern nuclear power plants are not applicable for this study. The deconstruction activities have therefore been inventoried based on a single reference case only regarding which data could be obtained. The reference case used for the inventory analysis is taken as the Helsingin Energia's Hanasaari A power plant which was demolished some five years ago in Helsinki, Finland. The reference plant was an old hard coal power plant which differed from the studied plant in many ways.

[15] Fly ash and APC residues are assumed to be stabilized with cement. The use of cement increases the mass of disposed waste, which then again increases the total working time required for the disposal of the residues.

In the reference case the deconstruction process started with the planning and licensing of the deconstruction activities. The second step was the emptying of process equipment and disconnecting the power plant from electricity and district heat grids. After that, the power plant was dismantled. The dismantling of power plant was started with the removal of asbestos followed by the mechanical dismantling of power plant structures. The waste originating from the deconstruction activities was sorted on site parallel to the deconstruction itself and transported to a further location for recycling or disposal. Finally, the underground structures were dismantled and recycled. (Taivainen 2012)

Alternatively, the power plant could be dismantled also manually. Whereas the mechanical dismantling is carried out using heavy machinery, the manual dismantling is carried out by cutting the structures to pieces with cutting torches and other mainly hand-held tools. Both methods have their pros and cons: if the power plant is disassembled manually, some of the power plant components can be reused in other locations. If the plant is however dismantled mechanically, no parts can be reused. Manual dismantling on the other hand increases the costs, working time and also risks of the decommissioning. The mechanical disassembly is the method that is favored nowadays for both safety and cost reasons and was also applied for the Hanasaari A power plant. The studied plant is therefore assumed to be dismantled mechanically. (Taivainen 2012)

In this study all decommissioning activities except for the planning and licensing have been taken into account. The planning and licensing of the deconstruction activities have been assumed to account for very small impacts on both environmental and occupational health and has therefore been excluded from the study. Both the inputs and outputs, and occupational accidents related to each phase of the deconstruction have been discussed step by step in the following two chapters.

5.1.1.4.1 Input and output data

No inputs have been considered for the **emptying of process equipment** and disconnecting the power plant from electricity and district heat grids. The emptying of power plant equipment requires very little energy use and practically no material use and can therefore be safely assumed to account for no significant environmental impacts for that part (Taivainen 2012). The outputs have to be considered however, as they can include some hazardous substances. In the studied case the only outputs considered are the bed materials used in the gasifier, the amount of which have been taken as the maximum amount in the process as stated in the environmental permit. Any remaining flue gas cleaning chemicals are assumed to be collected and taken to another location for further use, and have therefore not been considered here. The bed materials are assumed to be disposed in a slag compartment of sanitary material landfill. The emissions resulting from the disposal of bed materials have been calculated similarly as the emissions from the disposal of incineration residues based on the chemical composition of bed materials. The bed materials are assumed to be transported to the landfill using trucks with over 32t maximum weight over the distance of 10km.

The only input associated with the **mechanical dismantling of power plant** is the fuel that is required for the operation of the machinery. In the case of the Hanasaari A power plant 4-5 heavy construction machines were used for the deconstruction. One of the machines was used for sorting the waste while the others were used for the dismantling itself. The machines were operated four days a week for about one year during which time all of the structures above ground were dismantled and the waste sorted for further transportation and recycling. On average, the deconstruction of power plant structures is estimated to last from ten to twelve months depending on a variety of factors. For this study the duration is taken as twelve months. (Taivainen 2012)

The time and therefore also the amount of fuel required for the dismantling of the power plant or any other construction depends foremost on the deconstruction method applied (manual or mechanical) (Taivainen 2012). The size of the power plant has only minor impact on the duration of the deconstruction activities as long as the plants are even roughly the same size (Taivainen 2012). The same amount of machinery and operating time is therefore assumed for the studied plant as for the Hanasaari A plant. Altogether this means the consumption of ca. 1750 MWh diesel (Taivainen 2012; Kellenberger et al. 2007, pp. 553-559). The production of diesel has been modeled based on data discussed in chapter 5.1.2.2.

The most significant outputs of the mechanical dismantling consist of the construction materials used for the power plant. Most of the waste can be recycled. In fact, 90% recycling rate is considered the minimum, and even over 99% recycling rates can be achieved. In the case of the Hanasaari A power plant only 0,5% of the materials were not recycled. The material that was not utilized consisted of asbestos, mixed waste and hazardous waste such as fluorescence tubes. All of the metals, concrete and brickwork were recycled. (Taivainen 2012)

For this study 100% recycling rates have been assumed for metals, concrete, brickwork, bitumen and ceramic parts. For glass, insulation materials and plastics the recycling rate is taken as 0% judging based on data regarding the reference case. Altogether this results in the recycling rate of ca. 99% which seems a realistic estimate judging by data regarding the reference case. The disposal and recycling of materials has been modeled based on data discussed in chapter 5.1.2.4. Transportation distance of 20 km is estimated for concrete, brickwork, bitumen and ceramics based on Doka (2009b). For metals waste the transportation is included in the recycling model and has not been separately studied here. For materials disposed in landfills the transportation distance is taken as 15 km based on Frischknecht and colleagues (2007). The trucks used for the transportations are assumed to have maximum weight of over 32 tons.

In addition to waste, some emissions to air originate from the disposal activities. The use of diesel in the machinery accounts for some emissions to air. Also the dismantling and crushing of concrete causes dusting (Taivainen 2012). The emissions originating from the operation of the machinery have been inventoried based on data provided by Kellenberger and colleagues (2007, pp. 553-559) for building machines. The formation of dust depends on for example the moisture of materials and wind speed. In the reference case the dusting was decreased by sprinkling and timing the operations so that they were not carried out under unfavorable wind conditions (Taivainen 2012). For this study the emission factors presented by Doka (2009b) have been used as no more accurate data is available. The formation of dust also makes it that the actual recycling rates fall a bit behind the theoretical 100% recycling rates. Although the difference is not notable, it has to be taken into account in any case.

The **deconstruction of the underground structures** is the final step of the deconstruction activities. The dismantling of concrete foundations is not required in all cases but it was still carried out in the case of Hanasaari A power plant to avoid restricting future land use (Taivainen 2012). It has also been assumed to be carried out in the case of the studied plant. The dismantling lasted for three months requiring the use of similar equipment as the dismantling of the plant itself (Taivainen 2012). The inputs associated with the process have been calculated similarly as for the deconstruction of the structures above ground. This results in the fuel consumption of ca. 400 MWh diesel. The recycling of waste has been inventoried using the recycling rates discussed earlier for concrete. The dusting from the dismantling activities has been inventoried using the emission factors proposed by Doka (2009b).

In addition to the dismantling of concrete foundations, the excavation of some contaminated soil may be needed (Taivainen 2012). The possible contamination of soil is however extremely difficult to assess and has therefore not been considered here.

A summary of the material flows resulting from the deconstruction of the power plant is given in table 5.6. Table 5.6 covers all construction materials used for the power plant as discussed earlier in chapter 5.1.1.1.

Table 5.6. *Summary of the material flows resulting from the deconstruction*

Construction material	**To recycling**	**To final disposal**	**Dust to air**
Steel [ton]	9136	0	0
Concrete, brickwork, bitumen and ceramics [ton]	30489	0	5[1]
Other materials [ton]	0	438	0

[1]51% PM>10, 49% PM2,5-10, 10% PM<2,5

5.1.1.4.2 Occupational accidents and commuting accidents

The **emptying of process equipment** is expected to last between one and two months (Taivainen 2012). The work is done by the operating and maintenance staff of the power plant; no additional workforce is required to carry out the related tasks (Taivainen 2012). The overall working time is therefore taken as 11400 hours. The amounts of accidents associated with the work have been calculated based on the average accident frequency in the energy sector.

The **mechanical dismantling** of both power plant and its underground structures is considered a relatively safe operation. The dismantling is carried out using heavy machinery which is protected from possible falling debris. During the entire deconstruction of the Hanasaari A power plant two accidents occurred, neither of which resulted in absence from work. The deconstruction employed on average some eight to ten people working four days a week for a total of 15 months. (Taivainen 2012)

In this study the accidents associated with the deconstruction of both the power plant and the underground structures have been calculated based on the average accident frequency in the construction sector. The working time has been estimated the same as for the reference case (calculated assuming ten people working four days a week for 15 months). The amount of accidents indirectly associated with the deconstruction activities have been calculated using the data for the specific processes discussed in chapters 5.1.1.3 and 5.1.2.4 for waste treatment and in chapter 5.1.2.2 for energy production. The amounts of accidents directly associated with the mechanical dismantling are given in appendix C (table C3).

5.1.2 Background-processes

5.1.2.1 Transportation processes

5.1.2.1.1 Input and output data

The environmental impacts of transportation processes have been calculated based on data reported in the ecoinvent database for road and data reported in GaBi database for rail transportations. The size of vehicle used for the transportation is estimated based on data given in ecoinvent database for similar processes. For example, the size of trucks used for transporting the ashes from the gasification plant to disposal site has been estimated based on data given in ecoinvent database for average waste incineration plants. If no information regarding the size of truck is available, trucks with 16-32t maximum weight have been assumed for short distance transportations (<50km) and trucks with over 32t maximum weight for long distance transportations (≥50km).

For long distance transportation the transportation effort of one ton-kilometer (tkm) is associated with 0,0856km distance driven with the vehicle. For short distance transportation the transportation of one tkm equals to 0,173km driven with the vehicle. All trucks used for the transportation are assumed to meet EURO 4 emission standards. (Spielmann et al. 2007, pp. 90-96)

For the rail transportations an average mix according to the type of energy source used is established. 85% of the rail transportations in Finland are assumed to be carried out using electricity driven trains and 15% using diesel driven trains. The shares correspond to the average situation in Finland (VR Group 2012). In EU-15 area the shares have been taken as 64% and 36% as reported by Spielmann and colleagues (2007, pp. 106-108).

All water transportations have been approximated by a heavy fuel oil driven transoceanic freight ship. In reality there are numerous different types of freight ships being used (e.g. Spielmann et al. 2007). As the contribution of water transportation to the studied environmental impacts is expected to be small, and as only a few water transportations have been identified, no more detailed data is considered necessary. For water transportations also the operations taking place in the harbors are considered as reported by Spielmann and colleagues (2007, pp. 189-193). Other inputs related to for example the manufacturing and maintenance of ships have not been considered.

Transportation distances have been estimated based on information provided in the ecoinvent database for similar processes if no case specific information has been available. In case there is no information available that can be used to approximate the transportation distances, the standard distances reported by Frischknecht and colleagues (2007, pp. 12-14) have been used.

5.1.2.1.2 Occupational accidents and commuting accidents

The amounts of **accidents related to road transportations** have been calculated based on the working time required for the transportation of one ton goods over the distance of one kilometer (tkm). The working time is calculated using equation (15), where $WH_{haulage}$ is the working time relative to haulage of one tkm, V_{total} is the total haulage of professional road transportations in Finland during 2005-2009, and $WH_{tot,R}$ the total amount of working hours related to road transportations. The amount of working hours has been calculated using equation (16), where $WH_{tot,TR}$ is the total amount of working hours in the field transportation and storage (NACE H), $Workers_{tot,TR}$ the respective amount of workers and $Workers_{tot,R}$ the total amount of people working with road transportations.

$$WH_{haulage} = \frac{WH_{tot,R}}{V_{total}} \tag{15}$$

$$WH_{tot,R} = \frac{WH_{tot,TR}}{Workers_{tot,TR}} * Workers_{tot,R} \tag{16}$$

The values of variables needed for equations (15) and (16) are given in table 5.7. All values given in table 5.8 include both employees and entrepreneurs, but exclude private transportations.

Table 5.7. *Total haulage, amount of workers, average working time per worker and average working time per haulage for Finnish truck transportations in 2005-2009 (Statistics Finland 2008c; 2009b; 2009c; 2010b; 2011c; 2012b)*

Year	**Total haulage [tkm]**	**Workers [pcs]**	**Average working time / worker [h/pcs]**	**Average working time / haulage [h/tkm]**
2005	25332000000 (L)	39600 (L)	1907 (L)	0,002982 (SC)
2006	23366000000 (L)	40300 (L)	1930 (L)	0,003329 (SC)
2007	23454000000 (L)	42900 (L)	1918 (L)	0,003508 (SC)
2008	25362000000 (L)	43200 (L)	1898 (L)	0,003233 (SC)
2009	22049000000 (L)	39100 (L)	1833 (L)	0,003251 (SC)

The average working time per haulage for years 2005-2009 is ca. 0,0033h/tkm. Multiplying this with the accident frequency for transportations and storage results in values given in table C4 in appendix C. The amounts of accidents in EU-15 area have been calculated based on the average accident frequency for NACE H sector in EU-15 area and the working time given in table 5.7.

The amounts of accidents given in table C4 have been calculated based on the accident frequency for employees. It should be noted that as a large share of workers are actually entrepreneurs, the accident frequency used for trucking may not be accurate (Statistics Finland 2009b; Statistics Finland 2011b). This will probably also lead to an overestimation of the amounts of accidents related commuting, as the entrepreneurs can be expected to live closer to work place than average employees.

The accidents related indirectly to transportations are partially included in this study: the accidents related to the production of fuel are included in the study, but the accidents related to the manufacturing and maintenance of infrastructure and vehicles have not been taken into account. The amounts of occupational accidents have been calculated based on the amounts of accidents associated with the production of diesel as reported in GaBi databases and the average consumption of diesel as reported by Spielmann and colleagues (2007). The amounts of accidents related to travelling have been calculated based on the average working time reported in GaBi and average accident frequency for commuting accidents in EU-15 area. The amounts of indirect accidents relative to haulage are also given in table C4 in appendix C. The amounts of accidents have been calculated separately for long and short distance transportations as the fuel consumption is considered different depending on the vehicle used and distance driven.

The occupational **accidents related to rail transportations** have been modeled based on data given in GaBi databases. Accidents related to commuting have been modeled based on average working time associated with transportations as reported in the database, and the average national accident frequency. The amounts of occupational accidents and accidents related to commuting are given in table C4 in appendix C for rail transportations both in Finland and in EU-15 area.

The **accidents associated with water transportations** have been estimated based on data reported for Denmark in 2005-2008. The period of time and geographical location is taken as the reference for this study due to data availability reasons. The working time associated with water transportations have been calculated assuming an annual total of 64850 working hours per ship and an average annual haulage of 3,25E+9 tkm per ship (Danish Maritime Authority 2009; Spielmann et al. 2007). Based on this, the average working time required for the transportation of one ton cargo over the distance of one kilometer is set as 2,00E-5 hours per tkm. The accident frequency for non-fatal accidents is set as 9,47 and the accident frequency for fatal accidents as 0,0365 (calculated based on data reported by the Danish Maritime Authority (2009) for ships listed in the Danish international shipping registry). It should also be noted that both the working time and the accident frequencies are lower for Danish merchant fleet than for some other fleets in other parts of the world (Hansen et al. 2002; International Association of Oil & Gas Producers 2010). For this study this should not be a problem, as all of the water transportations that have been separately inventoried take place in Europe and can very well be operated by Danish ships. In case other regions are to be studied or if the water transportations are significant contributor to the outcomes of the study, more geographically accurate data is needed however.

The accidents related to commuting have been inventoried based on average accident frequencies for EU-15 region. The actual frequencies of commuting accidents are probably lower in the field of water transportations than on average as the employees are spending long non-stop periods of time onboard without being exposed to commuting accidents. The difference should not however be too significant to prevent from using the average data, as can be concluded based on data reported by Eurogip (2009b) for Spain. Again, in case the water transportations are significant contributor to the outcomes of the study, more accurate data has to be collected.

In addition to the accidents directly associated with the transportation of goods, also the accidents associated with the loading of ships as well as other operations taking place in the harbor have to be taken into account. For this study the working time associated with harbor operations is taken as 0,131 h/ton of throughput based on data reported for the port of Rotterdam during the time period of 2005-2009 (Port of Rotterdam 2011a; Port of Rotterdam 2011b). With an average transportation distance of 5000 km the working time corresponds to 2,62E-5 hours per tkm of haulage (Spielmann et al. 2007). The working time has been calculated considering the working time associated with navigation, storage and supporting services for transportation but excluding working time associated with road, rail and pipeline transportations, as these have been included in the respective processes. The amounts of accidents have then been calculated based on the working time given above and accident frequency for NACE H sector in EU-15 area.

Finally, the indirect accidents that need to be also covered are those related to the production of energy needed both in the harbors and on the vessels. The energy consumption for both harbors and vessels is inventoried based on data reported by Spielmann and colleagues (2007, pp. 171-195). Other indirect accidents related to for example the manufacturing of ships and equipment in harbors have not been considered in this study. The amounts of accidents associated with all aspects of water transportations discussed above are given in appendix C (table C4).

5.1.2.2 Production of energy

Three different types of energy consumption can be identified for the product life cycle: consumption of electricity, heat and transportation fuels. In addition, the consumption of some other fuels may occur during for example the production of materials, but these have been included in the respective datasets.

The production of electricity is modeled based on Finnish or European grid mix as given in the GaBi database depending on the location of consumption. Also other local grid mixes can be used in case some specific processes are known to take place in other regions and are expected to be significant contributors to the overall results of the study. The production of transportation fuels, in this case diesel, is also modeled based on average data given in GaBi databases. The production of district heat is modeled based on average Finnish district heat production mix as reported by Statistics Finland. In case heat is consumed in other regions than Finland, the production method proposed in ecoinvent reports for the specific process is used. The environmental impacts of different heat production methods have been modeled based on data given in GaBi and ecoinvent databases.

5.1.2.2.1 Input and output data

The input and output data given in GaBi database for the Finnish and European **electricity grid mixes** is used for this study. The Finnish grid mix is used for processes taking place in Finland while the European grid mix, in this case EU-27 grid mix as no other regional data is available, is used for processes taking place in other regions.

The inputs and outputs related to the **production of heat** in Finland have been inventoried based on data regarding the use of fuels for district heating. The input and output data for the district heat mix is calculated as the weighted average of each fuel type’s input and output data based on the usage of different fuels in Finland during 2005-2009. The use of different fuels is illustrated in figure 5.4.

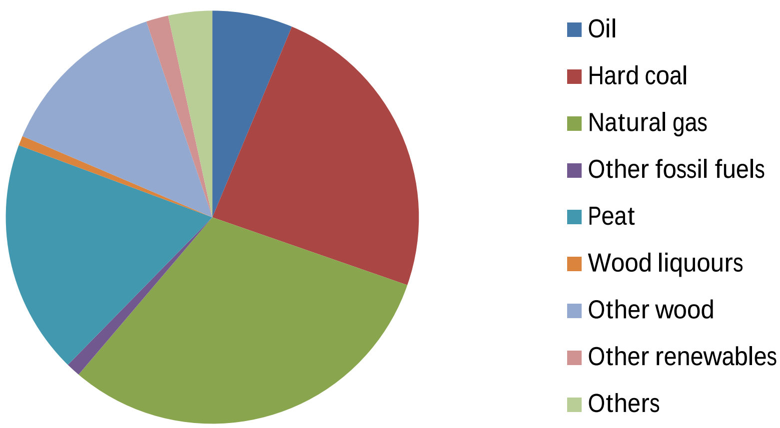

Figure 5.4. *Use of fuels for district heating in Finland in 2005-2009 (Statistics Finland 2010c)*

For oil (approximated by heavy fuel oil), hard coal and natural gas the input and output data given in GaBi database is used. The inputs and outputs associated with the production of heat from peat have been inventoried based on data given in ecoinvent database for the use of peat in power plants. The data given in ecoinvent database for the use of wood chips is used as proxy for all wood based fuels as no more accurate data can be easily obtained for this study. Both peat and wood area assumed to be used in cogeneration plants, and the inputs and outputs have to be therefore either allocated to different products (i.e. heat and electricity) or the allocation has to be avoided by system expansion. Given the fact that inputs and outputs have been allocated to other heat production methods described in GaBi database, system expansion would actually make it that the modeling principles would be inconsistent for different heat production methods. Therefore, the inputs and outputs have in this case been allocated to heat and electricity. An exergy based method described by European Commission (2010e) is used for allocating the inputs and outputs to electricity and heat. Initial data published by Statistics Finland (2010c) and Finnish Environment Institute (2001) is used to calculate the allocation factors (2,74 for electricity and 0,396 for heat).

The data given in both ecoinvent and GaBi databases is reported for the *production* of energy. In order to determine the actual inputs and outputs for the *use* of heat, one has to consider also the transition losses. In Finland the average transition loss for district heat is 9%, meaning that in order to be able to use one MWh of heat 1,1 MWh of heat has to be produced (Honkapuro et al. 2009, pp. 35). All of the inputs and outputs given in GaBi and ecoinvent database have therefore been multiplied by a factor of 1,1 to consider the actual impacts of the consumption of heat rather than its production.

The inputs and outputs related to the **production of fuels** have been inventoried based on data given in GaBi database for the respective fuel. The inputs and outputs associated with the **use of the fuel** in machinery have been inventoried based on data provided by Kellenberger and colleagues (2007, pp. 553-559) for the use of fuel in building machinery in case no data regarding the specific machine in which the fuel is used is available or the specific type of machine is unknown. This is done following the basic assumptions in ecoinvent database, where the process is taken as a proxy for most diesel using machinery.

5.1.2.2.2 Occupational accidents and commuting accidents

The occupational accidents related to the Finnish and European **electricity grid mixes** have been inventoried based on data given in GaBi database for the specific processes. The amounts of associated commuting accidents have been calculated based on working time data given in GaBi database and average accident frequency for commuting accidents in EU-15 region.

The occupational and commuting accidents related to heat production have as a rule been inventoried based on data provided in the GaBi database for different sources of heat. Peat and partially biomass however form an exception to the rule. GaBi database does not contain information about the use of peat or biomass for the generation of heat, and the data has to be therefore collected separately for this study.

Occupational accidents related to the **production of energy from peat** have been calculated assuming 0,138 direct and 0,127 indirect working hours for the production of 1MWh peat as well as 0,074 direct and 0,143 indirect working hours for the use of 1MWh peat in power plants. The working hours have been calculated based on values reported by Flyktman (2009) and Statistics Finland (2012b). The value used here for the working time associated with the operation of the power plants is different from what is estimated for the studied gasification plant. This can be the result of both different assumptions made when collecting the initial data given in literature, or the result of studying plants with different capacities and annual operating times.

The amounts of accidents associated with the transportation of peat have been calculated using the generic transportation processes described in chapter 5.1.2.1. The haulage associated with the transportation of one MWh peat is calculated as 32,4 tkm based on values reported by Flyktman (2009).

Amounts of accidents related to the production and use of peat are presented in table C5 in appendix C. National average accident frequency is used for calculating the amount of indirect accidents. Direct accidents have been calculated based on the accident frequency of the specific industry sector (NACE2 B for the production and NACE2 D for the use of peat). Accidents have been allocated to electricity and heat similarly as input and output data.

Occupational accidents related to the **production of energy from wood based fuels** have been calculated similarly as for peat. Working time associated directly with the acquisition and production of wood based fuels is taken as 0,33h/MWh based on data reported by Halonen and colleagues (2003), Koisti (2011), and Pöyry Forest Industry Consulting Oy (2006). The working time associated indirectly with the acquisition and production of wood is estimated as 30% of the direct working time based on data reported by Koisti (2011) and Pöyry Forest Industry Consulting Oy (2006). The working time associated directly and indirectly with the use of wood in power plants is estimated as the same as for peat. The working time and amount of accidents associated with the transportation of wood has been calculates assuming 20tkm haulage per one MWh wood.

Amounts of accidents related to the production of energy from wood based fuels are presented in table C5 in appendix C along with the accidents associated with the energy production from peat. Accidents associated with the production and use of wood have been calculated based on the accident frequency of the specific industry sector (NACE2 A for the production of wood and NACE2 D for the use of it). The amounts of indirect accidents have been calculated based on average accident frequency for NACE2 A-F and H sectors in EU-15 area. Accidents have been allocated to electricity and heat similarly as input and output data.

The amounts of accidents associated with **average heat production in Finland** can be calculated by combining the data given in appendix C for peat and wood based heat production chains, and data given in GaBi databases for other energy sources. To consider also the transition losses, the data has to be multiplied by a factor of 1,1 to determine the accidents associated with the production of usable heat. The corrected amounts of occupational and commuting accidents associated with the production of heat in Finland are given in table C5 in appendix C.

The occupational accidents associated with the **production of fuels** have been inventoried based on data reported in GaBi database for the specific type of fuel. The amounts commuting accidents have been calculated based on the working time reported in GaBi and the average accident frequency for commuting accidents in EU-15 region. The occupational accidents associated with the **use of fuels** have in all cases been allocated to the value adding process. For example the occupational accidents associated with the use of fuel in the preparation of REF have been allocated to the process of REF preparation.

5.1.2.3 Production of materials

5.1.2.3.1 Input and output data

The input and output data related to the production of different materials needed during the processes included in this study is inventoried in all cases based on data available in GaBi and ecoinvent databases.

For some materials no data is available in the available databases. In such case best representative or average data has been used. These materials have been given in table 5.8 below along with the processes that have been used to approximate their input and output data.

Table 5.8. *Materials for which no data is available in GaBi or ecoinvent databases and that have therefore been modeled based on best representative data*

Material	**Best representative material**	**Source of data**
Liquefied petroleum gas (LPG)	Propane / butane	Ecoinvent
Paint	Organic chemicals (unspecified)	Ecoinvent
Sodium hydroxide	Inorganic chemicals (unspecified)	Ecoinvent
Activated carbon	Inorganic chemicals (unspecified)	Ecoinvent

The production of cement that is needed for e.g. the stabilization of incineration residues is inventoried based on data reported by Finnsementti (2012a, pp. 27). The mining and processing of hard coal needed during the production of cement is modeled based on data described in chapter 5.1.3.2. The recycled fuels consumed during the production of cement have been considered as REF. The preparation of REF has been considered as discussed in chapter 5.1.2.5. Gravel is taken as proxy for diabase, and inorganic chemicals as proxy ferrous sulfate as no case specific data is available. All of the inputs and outputs reported by Finnsementti (2012a, pp. 27) have been allocated to cement.

5.1.2.3.2 Occupational accidents and commuting accidents

Occupational accidents related to the production of materials have been inventoried based on the data given in GaBi database (if available). The amounts of commuting accidents have been calculated based on the working time reported in GaBi and the average EU-15 accident frequencies.

For the processes that have been modeled based on data from ecoinvent database no working time data is available. For these processes the amounts of occupational accidents have therefore been estimated based on the best representative data that is available in the databases. The materials for which no working time or accident data is reported includes those materials given in table 5.8 in previous chapter, and concrete.

For the **materials listed in table 5.8** the amounts of occupational accidents have been calculated based on a mix of most produced organic and inorganic chemicals, and a mix of organic solvents. These mixes have been used to approximate the accidents associated with the production of other chemicals for which no case specific data is available.

In ecoinvent database both unspecified organic and unspecified inorganic chemicals as well as unspecified solvents consist of the mix of twenty most produced organic or inorganic chemicals and solvents. The accident and working time data for these mixes have been calculated as the average of those compounds, regarding which data is available in GaBi database. Nine different inorganic chemical compounds have been used for calculating the accident and working time data for unspecified inorganic chemicals. For unspecified organic chemicals the data is calculated based on 11 different chemicals and for organic solvents based on seven different chemicals. A list of the chemicals that have been used for estimating the amounts of accidents and working time associated with the production of unspecified chemicals and solvents are given in table 5.9. The amounts of accidents associated with the production of unspecified chemicals and solvents have been given in table C6 of appendix C.

Table 5.9. *Chemicals used for estimating the working time and accident data of unspecified chemicals and solvents*

Organic chemicals	Inorganic chemicals	Organic solvents
Chlorine	Acetic acid	Acetone
Hydrochloric acid	Acetone	Cumene
Hydrogen fluoride	Butadiene	Ethylene glycol
Nitric acid	Ethylene glycol	Isopropanol
Nitrogen	Ethylene oxide	Nitrobenzene
Soda	Formaldehyde	Styrene
Sodium hydroxide	Phenol	Toluene
Oxygen	Styrene	
Ammonia	Toluene	
Quicklime	Benzene	
	Propene (propylene)	
	Vinyl chloride	

For the **production of concrete** no data exists in the GaBi database that could be used for estimating the amounts of occupational and commuting accidents related to its production. The amounts of accidents have therefore been estimated by dividing the number of fatal accidents that are reported by Schmidt et al. (2004) to be associated with the production of concrete by the average accident frequency (for NACE A-F and H sectors in EU-15 area) to determine the average working time. The amounts of occupational and commuting accidents have then been calculated based on this estimated working time and the average accident frequency. The amounts of accidents associated with the production of concrete are given in appendix C (table C6).

The occupational and commuting accidents associated directly with the **production of cement** have been inventoried assuming 0,25 working hours per the production of one ton cement (Finnsementti 2012a, pp. 27; Finnsementti 2012b). The indirect accidents related to the production of cement have been inventoried by combining the accident data from all of the supporting processes. The accidents associated with the production of raw materials needed for the production of cement have been inventoried as discussed in this chapter, and the accidents from the production of energy as discussed in chapter 5.1.2.2. The accidents from the transportation and production of hard coal have been inventoried using the data discussed in chapter 5.1.3.2. A summary of accidents associated directly with the production of cement is given in appendix C (table C6).

For the **production of glass** used in windows no data is available to support the calculation of accident data. The **accidents associated with the production of glass have therefore not been considered** here.

5.1.2.4 Generic waste management processes

5.1.2.4.1 Input and output data

Five different types of generic waste management processes have been considered in this study:

- Recycling of steel waste
- Recycling of concrete, brickwork and other ceramic materials
- Disposal of unspecified waste in landfills
- Incineration of unspecified waste in municipal solid waste incinerator
- Incineration of unspecified hazardous waste

The recycling and waste incineration processes with energy recovery have been inventoried as closed-loop processes as described in figure 5.5 below. The closed-loop recycling means that any valuable goods produced during the disposal process are used to replace virgin materials in other parts of the value chain. The closed-loop recycling is used for both material recycling and energy recovery.

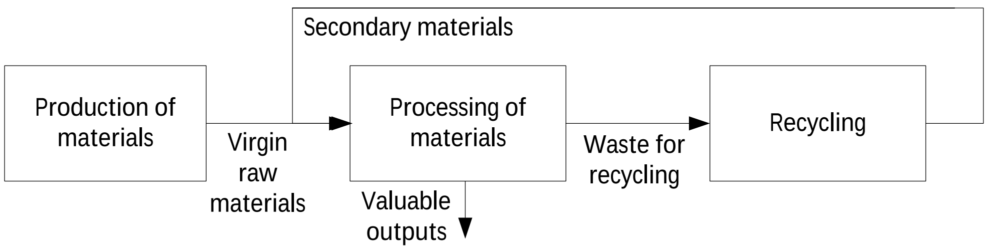

Figure 5.5. *A material flowchart for closed-loop recycling*

The inputs and outputs related to most of the recycling and disposal processes have been inventoried based on data given in GaBi database. Data provided by Worldsteel is used for modeling the **recycling of steel**. The **landfilling of unspecified waste** is modeled based on average landfilling of commercial waste in Europe, and the **incineration of waste** is modeled based on data reported for average incineration of municipal solid waste (MSWI) in Europe. The **incineration of hazardous waste** (HWI) is modeled based on data reported in ecoinvent database. Also some waste specific disposal processes have been used for example for the disposal of concrete in landfills. These have in all cases been modeled based on data given in either GaBi or ecoinvent database.

The **recycling of concrete** has been modeled assuming that the concrete waste is used as foundation for roadway pavement, which is one of the most common uses of recycled concrete (Vakkuri 2011). The recycled concrete is assumed to replace the use of natural gravel, which is the primary material used as foundation for roadway pavement (Vakkuri 2011; Spiellman et al. 2007, pp. 76-77). In many cases the use of concrete waste for foundations of roadway pavement reduces the use of natural gravel by more than its weight as it has numerous beneficial properties compared to natural gravel (Vakkuri 2011). Here the ration of recycled concrete and replaced gravel is however taken as one to one. All of the recycled concrete that has been considered in this study originates from the deconstruction of the power plant infrastructure. The crushing of concrete has been inventoried as a part of the deconstruction activities and has therefore not been separately considered for the recycling process. The sorting of concrete has not been considered here, which will result in slight overestimation of the benefits of recycling. This is not however significant regarding any outcome of this study.

5.1.2.4.2 Occupational accidents and commuting accidents

The occupational accidents related to all **landfilling processes** have been inventoried based on data given in GaBi database for the landfilling of commercial waste. The commuting accidents have been inventoried based on working time data reported in the GaBi databases and average accident frequency for commuting accidents in EU-15 area. No difference is made between the disposals of different types of waste or different types of landfills.

The occupational accidents associated with the **recycling of steel** scrap have been inventoried based on data given in GaBi database for the closed-loop recycling of steel. The commuting accidents have been inventoried based working time data reported for the recycling process and average accident frequency for commuting accidents in EU-15 area.

No data regarding the accidents associated with the **incineration of (municipal solid) waste** is available in GaBi databases. The amounts of accidents have therefore been roughly estimated based on data given in literature. The amounts of accidents directly associated with MSWI have been calculated based on the average working time associated with the operation of waste incineration plants and average accident frequency for NACE D sector (all waste incineration plants have been treated as energy recovery plants). The working time has been estimated as ca. 0,14 h/t waste based on values reported for a number of new Finnish power plants (Lahti Energia 2005; Oulu Energia 2004; Seinäjoen Energia Oy 2004; Porin Lämpövoima Oy 2004; Vapo Oy 2006). The accidents indirectly associated with MSWI have been inventoried based on the input and output data reported for the incineration process by Doka (2003), and the accident and working time data for the specific processes delivering the required inputs or treating the outputs as given in GaBi database. The accidents associated with the incineration of the power plant infrastructure have in this case not been considered. A summary of the accidents associated with MSWI is given in table C7 in appendix C.

There is no accident or working time data available regarding the **incineration of hazardous waste** either, so also that data has to be acquired from other sources. The same approach has been used as in the case of MSWI. The direct working time is taken as the same as for MSWI, and the indirect accidents have been inventoried using the same approach and data sources. A summary of the occupational and commuting accidents associated with HWI is given in table C7 in appendix C alongside the accidents related to MSWI.

The amounts of occupational accidents associated with the **recycling of concrete** have been estimated based on the data reported in GaBi database for the production of gravel. The accidents associated with the crushing of concrete have been calculated as a part of the deconstruction activities discussed in chapter 5.1.1.4. The accidents associated with the sorting of crushed concrete have not been considered here.

5.1.2.5 Production of REF

5.1.2.5.1 Input and output data

The production of REF takes place mainly in Kujala waste processing plant, which is located ca. 9 km from the waste incineration plant. Waste is crushed and metals as well as other materials not suitable for the incineration are separated from the waste in the processing plant. Material yield of the processing varies between good 40% and almost 100% with residues including both valuable materials (e.g. metals) and waste (Ajanko et al. 2005; Ekholm et al. 2005). The yield of the process is affected by the type of waste being processed (Ekholm et al. 2005). In general, the best yield can be achieved when preparing waste from separately collected energy fraction (Myllymaa et al. 2008, pp. 17-19; Ajanko et al. 2005). For this study 93% yield is estimated, with the remaining 7% consisting of collected metals, reject and evaporated water. Crushing and conveying of waste can be expected to cause some dusting, which can however be significantly reduced by performing the operations indoors.

The processing requires some energy for e.g. the operation of crushers and magnetic separators. The energy consumption is affected by the type of waste being processed. The electricity consumption of REF preparation is reported to vary between 29 kWh 56 kWh per ton of REF depending on for example the properties of waste as well as the type of processing and equipment used for it (Myllymaa et al. 2008, pp. 17-19; Heikkinen et al. 2002, pp. 35-38, pp. 35-38; Tsupari et al. 2005). For this study electricity consumption of 36,45 KWh per ton of REF is assumed based on Myllymaa and colleagues (2008, pp. 17-19), since it most accurately describes the processing required for the studied fuel mix.

Besides electricity, also diesel and according to Myllymaa and colleagues (2008, pp. 17-19) thermal energy is needed for the preparation of REF. Diesel consumption associated with the preparation of REF is ca. 4,81 kWh per ton of REF as calculated based on information provided by Heikkinen and colleagues (2002, pp. 35-38), and Kellenberger and colleagues (2007, pp. 553-566). The consumption of thermal energy on the other hand is ca. 23,06 kWh per ton of REF as reported by Myllymaa and colleagues (2008, pp. 17-19). Thermal energy required for the preparation of REF is treated as district heat.

Mass and energy balance of REF preparation is presented in table 5.10. The environmental impacts resulting from the production of electricity and heat are modeled as reported in chapter 5.1.2.2. The environmental impacts of diesel used in tractors and other machinery is modeled based on data provided by Kellenberger and colleagues (2007, pp. 553-566) for skid-steer loaders.

Table 5.10*. Mass and energy balance of REF preparation (Myllymaa et al. 2008, pp. 17-19; Heikkinen et al. 2002, pp. 35-38; Kellenberger et al. 2007, pp. 553-566; own assumptions)*

Inputs		**Outputs**	
Energy fraction from industry	1,075 t (L)	REF	1,000 t (L)
Electricity	36,45 kWh (L)	Metals	0,011 t (L)
Thermal energy	23,06 kWh (L)	Reject (to landfill)	0,032 t (L)
Diesel (used in tractors etc.)	4,81 kWh (L)	Evaporated water and dust	0,032 t (A)

5.1.2.5.2 Occupational accidents and commuting accidents

According to the NACE2 classification, the preparation of REF is included in the NACE2 E sector. The accident frequency in the specific sector is notably greater than the average accident frequency in Finland, or the average accident frequency of manufacturing industries. According to Heikkinen and colleagues (2002, appendix 8), the accident frequency for REF preparation should however be lower than the average accident frequency for manufacturing industries. The accident frequency for manufacturing industries instead of that for the waste management sector has therefore been used as an upper limit estimate for calculating the accidents associated with the preparation of REF.

The average working time associated with the production of recycled fuels was some 0,9h/ton REF in 2001 including also the transportation of REF from production site to the power plant (Halonen et al. 2003, pp. 31-32). By 2010 the average working time was expected to be reduced to some 0,7h/ton REF following the increased production of recycled fuels. Also notably smaller working times have been reported for the production of recycled fuels; Heikkinen and colleagues (2002, pp. 35-38) for example estimated that the production of one ton REF would be associated with some 0,2 hours of work excluding working time associated with transportations. On the other hand the REF production plant in Kerava, which is taken as the reference for the production plant being built to produce REF for the studied gasification plant, employs some 70 people and produces about 100000 tons of REF (Lahti Energia 2005; Vesanto et al. 2007, pp. 14). All in all, the working time associated with the production of one ton REF is reported to vary between ca. 0,2 and 1,2 hours per one ton of REF. For this study the working time is taken as the average of smallest and biggest value given in literature, i.e. 0,7 h/ton REF. Multiplying this with the accident frequencies for manufacturing industries (NACE2 C) results in the amounts of accidents given in table C8 in appendix C.

In addition to the accidents resulting directly from the preparation of REF, a number of accidents is also associated with the process indirectly. The production of electricity, heat and diesel used in the machinery is expected to cause some accidents. The accidents related to the production of energy carriers have been calculated as discussed earlier in chapter 5.1.2.2 based on the consumption of energy given in table 5.10.

5.1.3 Replaced sources of energy

For this study the replaced energy production method is taken as hard coal used in a large combined heat and power (CHP) plant in Finland. The CHP plant is assumed to have the same characteristics as the studied waste gasification plant, i.e. overall efficiency of ca. 88% and power to heat ratio of ca. 0,56. These are typical characteristics also for hard coal CHP plants: in Finland the average efficiency of all CHP plants was ca. 85% in 2010, and the power to heat ration ca. 0,5 (Statistics Finland 2011d). In district heating applications power to heat ratios closer to 0,6 are typical (Finnish Environment Institute 2001). For this study an average 460 MW power plant has been considered (in terms of the infrastructure) as determined by Dones and colleagues (2007, pp. 99). During its life time, the power plant is estimated to use ca. 69 TWh of hard coal and deliver some 61 TWH of utilizable energy.

Given the similar characteristics of alternate energy production method and the studied plant, there is no need for allocation. The environmental impacts of hard coal are calculated relative to one megawatt hour of fuel used in the power plant, which is equivalent with the gasification of 0,224 ton REF in the gasification plant (considering the produced electricity and heat).

The environmental impacts of the use of hard coal arise mainly from airborne emission from the power plant. In addition, the mining and transportation of hard coal, production and transportation of chemicals used in the power plant as well as disposal of ashes and the construction of needed power plant infrastructure cause some environmental impacts. These have been studied with the same system boundaries as the environmental impacts of the waste gasification plant. System flowchart of a typical hard coal CHP plant is illustrated in figure 5.6.

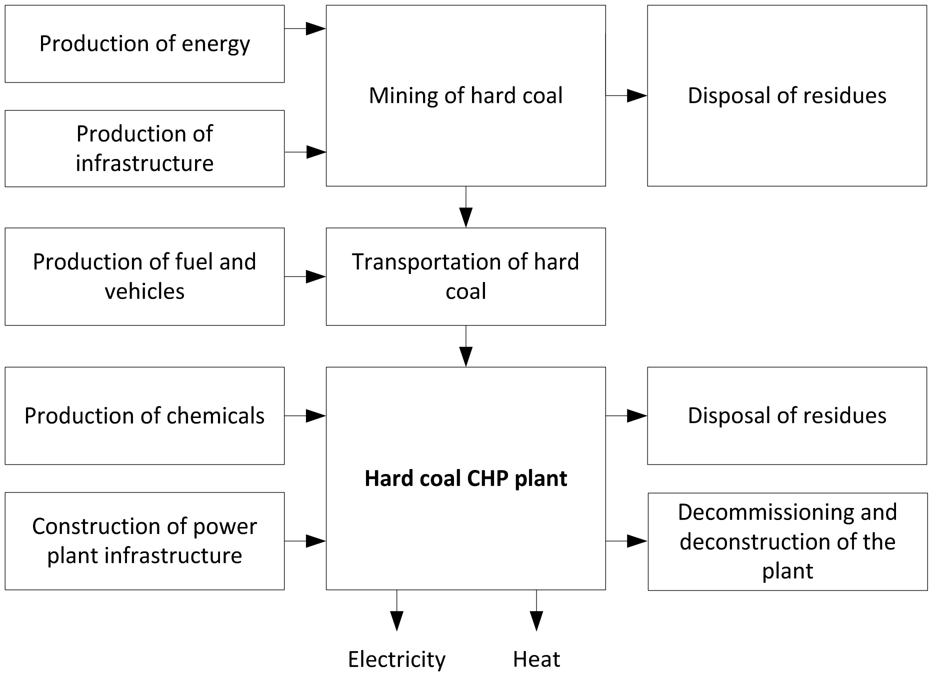

Figure 5.6. *System boundaries for the hard coal CHP power plant*

As the use of hard coal is estimated to be avoided over the entire life time of the studied plant, the data should be collected so that it is suited to represent the future situation. Basically this means that the data should represent future scenario data, BAT data or most recent data (European Commission 2010d, pp. 36). In the future the energy generation from hard coal is indeed expected to be cleaner than it is at the moment (e.g. Bauer et al. 2008). However, as the use of hard coal is avoided over the entire life time of the plant, it is safe to assume that the avoided burden comes from plants that are already in use, or that would be built if the gasification plant was not built. Here the first option is taken as the starting point, i.e. the avoided burden is assumed to come from existing plants. Therefore most recent data is used for the analysis. This is a fair assumption given that hard coal power plants typically have a notably longer life time than what is expected for the studied gasification plant (Dones et al. 2007, pp. 99; Bauer 2008, pp. 40). Therefore in order to be operational over the entire life time of the gasification plant, the hard coal power plant could at the moment very well be some fifteen years old.

5.1.3.1 Construction of the power plant

5.1.3.1.1 Input and output data

The construction of the power plant has been modeled based on data reported by Dones and colleagues (2007, pp. 99-100) taking into account the same limitations as in the case of the studied gasification plant. That is, for example the use of copper has not been considered as it has not been considered for the studied gasification plant either. The power plant consists mainly of different kinds of steel products similarly to the gasification plant. The foundation is built of reinforced concrete.

The amounts of different **materials used for the buildings and equipment** are given in table 5.11. The production of different construction materials has been modeled based on data reported in GaBi and ecoinvent databases for best representative products.

Table 5.11. *Construction materials used for the gasification plant (Dones et al. 2007, pp. 99-100)*

Material	**Mass [t]**	**Best representative process and source of data**
Steel, buildings and equipments	38400 (L)	Power plant component, Metso Power Tampere workshop (internal data)
Steel, concrete reinforcements	7450 (L)	Reinforcing steel (ecoinvent)
Concrete, foundations	149000 (L)	Concrete, normal (ecoinvent)
Insulations	571 (L)	Rock wool, 30-180kg/m³ (GaBi)
Plastics, buildings and underground structures	40 (L)	Polyethylene granulate
Bitumen	200 (A)[1]	Bitumen (GaBi)

[1]Estimated the same as for the gasification plant

The further processing of materials has been considered only for the steel parts, as is done also for the studied gasification plant. The steel parts are assumed to be pre-manufactured to different kinds of elements or power plant equipments. The pre-manufacturing is approximated in all cases based on data regarding the operations taking place in Metso Power's Tampere workshop (see appendix D). This is done to gain some information regarding the pre-manufacturing even though it is in reality a rather poor approximation of the actual inputs needed. It is nonetheless considered a better approach than the mere exclusion of the specific process from this study.

The energy consumption during the construction of the power plant is inventoried based on data reported by Dones and colleagues (2007, pp. 99-100). The waste formation is inventoried following the same assumptions as for the gasification plant. Data regarding energy consumption and waste formation is given in table 5.12.

Table 5.12. *Energy needed for the construction of power plant infrastructure, and an estimate of the waste produced during the construction processes*

Input / output	**Amount**	**Reference**
Diesel	64200 MWh (L)	Dones et al. 2007
Electricity	15000 MWh (L)	Dones et al. 2007
Light fuel oil	64200 MWh (l)	Dones et al. 2007
Excavated ground	169000 t (A)	Volume of excavated ground estimated as the same as the volume of concrete used for foundations. Density of excavated ground estimated as 2,7t/m3 based on Ronkainen (2012)
Packaging waste: steel	Based on internal unpublished data (A)	Estimated based on the use of packaging materials in Metso Power's workshops
Packaging waste: wood	Based on internal unpublished data (A)	Estimated based on the use of packaging materials in Metso Power's workshops

The construction of the plant causes some dusting as in the case of the studied gasification plant. Again no detailed information is available regarding the exact formation of dust due to construction activities. The dusting can be expected to be greater than in the case of the gasification plant following the greater amount of excavated soil. Here, it has been assumed that the **amount of dust emissions is twice the amount of dust emissions from the construction of the gasification plant**. This is again a pure assumption and has to be specified in case the dusting has a notable impact on the overall outcomes of this study.

5.1.3.1.2 Occupational accidents and commuting accidents

The amounts of occupational and commuting accidents related to the construction of the power plant have been inventoried following the same boundary conditions as in the case of the gasification plant: accidents have been considered only for the production of materials, pre-manufacturing of steel parts, transportation of materials and parts to the construction site and construction activities taking place on site.

The accidents associated with the production of materials have been inventoried based on data given in GaBi database or best representative data available in literature as discussed in chapter 5.1.2.3. The accidents associated with the transportation of materials to the construction site have been modeled using standard transportation distances reported by Frischknecht and colleagues (2007, pp. 12-14), and the average transportation processes.

The accidents directly associated with the pre-manufacturing of steel parts and equipment are inventoried based on Metso Power's internal data in order to ensure consistency with the data regarding the gasification plant. The amount of accidents associated with the pre-manufacturing of power plant equipment is given in table C9 in appendix C. The amount of indirectly associated accidents has been calculated based on data available in GaBi databases and literature for the energy and material production, and waste disposal processes as discussed in chapters 5.1.2.2, 5.1.2.3 and 5.1.2.4.

The amounts of accidents associated with the construction activities have been calculated by assuming 0,623 man-years working time per MW of fuel power. The working time has been calculated based on the reference plants discussed in chapter 5.1.1.1 **excluding the four plants for which exceptionally high working times have been reported**. These have been excluded from the calculations firstly to ensure a conservative approach regarding the overall outcomes of this study (i.e. to ensure that the human health impacts caused by the gasification plant are not underestimated), and secondly since the construction of hard coal power plants is expected to be better established process which is faced with less difficulties than the construction of unique solutions such as the studied gasification plant. Again the share of people building and installing the power plant equipments is taken as 50% of the overall working time, and the rest is taken as work done by people involved in the construction activities. The accident frequencies for workers involved in installing and building the equipments are taken as the accident frequency in Finnish manufacturing industries[16]. For the rest of the work, the average accident frequencies in Finnish construction sector have been used. The amounts of accidents for both categories of workers are given in table appendix C (table C9).

The accidents associated with the production of energy needed during the construction have been inventoried based on data given in GaBi for different energy production methods and waste disposal activities. These processes are discussed in detail in chapters 5.1.2.2 and 5.1.2.4.

5.1.3.2 Production of hard coal

5.1.3.2.1 Input and output data

Hard coal is assumed to be produced in Kemerovo Oblast region in Russia, where most of the coal used in Finland is produced (Mäkelä & Pöyhönen 2010, pp. 5). The inputs and outputs associated with the mining of hard coal have been inventoried based on data available in GaBi and ecoinvent databases.

Coal is assumed to be transported to the power plant by train. The distance is taken as roughly 3700km. Standard transportation process for EU-15 area is used for the train transportation. No case specific data for Russia is used as it is not available in the GaBi or ecoinvent databases. Even though also some road transportations are likely to take place, they have not been considered here.

5.1.3.2.2 Occupational accidents and commuting accidents

The working time directly associated with the mining of hard coal is taken as 0,359h/MWh fuel based on data regarding the employment in hard coal mining in six European countries and the average working time in the given countries (European Commission 2010f, pp. 10;

[16] The installation work is not considered construction activity as far as Metso is considered. Therefore, the accident frequencies for the manufacturing sector (NACE2 C) have been used.

Cabrita & Ortigão 2011). The working time indirectly associated with the mining of hard coal is taken as 1,3 times the direct working time, i.e. 0,467h/MWh fuel as suggested by European Commission (2010f, pp. 15).

The amounts of occupational and commuting accidents associated with the mining of hard coal have been calculated specifically for Russia. This is done by multiplying the average accident frequencies in EU-15 area with the correction factor for Russia, which is calculated using equation (4). The amounts of occupational and commuting accidents can then be calculated by multiplying the average working times with the specific accidents frequencies for Russia. The resulting amounts of occupational and commuting accidents are given in table C10 in appendix C for the mining of hard coal.

The calculated amount of accidents associated with the mining of hard coal can be expected to be quite close to the actual amount of accidents. Berry and colleagues (1995, pp. 143-144) for example report the number of fatal occupational accidents in the mining of hard coal to be 7,7E-8 fatality cases per MWh of fuel in the UK. Given that the general level of occupational safety in Russia is worse than in UK, the actual accident frequency should be slightly greater than the value reported by Berry and colleagues (1995, pp. 143-144) and also the value used for this study. On the other hand also notably smaller estimates have been presented by for example Schmidt and colleagues (2004) indicating that the uncertainties associated with the inventory data are notable.

The amount of accidents associated with the transportation of hard coal have been calculated using the data regarding average transportation processes given in chapter 5.1.2.1 for EU-15 area. The amounts of accidents have again been corrected using equation (4) as most of the transportations take place in Russia. The amounts of occupational and commuting accidents associated with the transportation of hard coal have been given in table C10 in appendix C. The values have been calculated based on the standard transportation processes that have been adjusted to consider Russian accident frequencies.

5.1.3.3 Operation of the power plant

5.1.3.3.1 Input and output data

The operation of the power plant results in both direct and indirect impacts on human health and environment. The direct inputs covered here are the emissions to air from the power plant. Emissions resulting from the combustion of fuel have been modeled based on data provided by Dones and colleagues (2007). **Only the emissions components covered in the inventory of the REF gasification plant have been considered.** Other emission components have not been considered to ensure the same scope as for the studied product system. The amount of emissions to air has been inventoried based on data given in ecoinvent database, EMEP/EEA air pollutant emission inventory guidebook and IPCC

GHG inventory guidelines[17]. For this study the smallest value given in above documents is used apart from CO_2, for which the IPCC value is used independent of whether or not it is the smallest reported value. The emissions resulting from the use of one MWh hard coal have been given in table 5.13.

Table 5.13. *Emissions from the combustion of hard coal*

Emission component	Average [kg / MWh fuel]	Reference
CO_2	341	Gomez et al. 2006
CO	0,0288	Trozzi et al. 2010
TOC	0,00792[1]	Gomez et al. 2006; Trozzi et al. 2010
NOx	0,221	Dones et al. 2007
SO_2	0,468	Dones et al. 2007
Dust	0,0295	Dones et al. 2007
HCl	0,0130	Dones et al. 2007
HF	0,00986	Dones et al. 2007
Dioxins and furans (as TEQ)	3,60E-11	Trozzi et al. 2010
Cd + Tl	3,26E-7[2]	Dones et al. 2007
Hg	5,33E-6	Dones et al. 2007
Sb+As+Pb+Cr+Co+Cu+Mn+Ni+V	3,74E-5[3]	Dones et al. 2007

[1]45% CH4
[2]Only Cd, no data regarding Tl available
[3]0,75% Sb; 2,89% As; 21,69% Pb; 2,28% Cr; 1,76% Co;24,18% Cu; 24,87% Mn; 16,57% Ni; 5,01% V

The emissions reported in table 5.13 may not be applicable in the future, as the emission intensities of large combustion plants can be expected to be decreased following the implementation of new emission limits in EU. The European directive 2010/75/EU on industrial emissions for example can lead to actual emissions being smaller than those given in table 5.13. Therefore the emission data used for this study is better suited to describe the current situation instead of future situation.

The indirect impacts result from the production and transportation of flue gas cleaning chemicals and other ancillary materials needed at the plant. Their consumption has been modeled based on data provided by Dones and colleagues (2007). Transportation distances described by Sorkka and colleagues (2005, pp. 21) have been assumed for ammonia, limestone and sodium hydroxide. Transportation distances described by Dones and colleagues (2007) and Frischknecht and colleagues (2007, pp. 12-14) have been used for other ancillary materials. The inputs related to the production of materials used at the power plant have been inventoried following the approach described in chapter 5.1.2.3.

5.1.3.3.2 Occupational accidents and commuting accidents

The accidents directly associated with the operation of the hard coal power have been calculated based on the working time data reported for Lahti Energia's hard coal power

[17] See Dones et al. 2007, Gomez et al. 2006 and Trozzi et al. 2010

plant. The working time is thus slightly lower than for the studied gasification plant, which is in line with the fact that large power plants require less workforce relative to the fuel use (Halonen et al. 2003, pp. 13-14). The amounts of occupational and commuting accidents associated with the operation of the power plant are given in appendix C (table C11).

The amounts of accidents associated with the production of materials needed at the power plant have been inventoried following the procedures described in chapter 5.1.2.3 for the production of different materials. The amounts of accidents resulting from the transportation of ancillary materials have been calculated using the standard transportation processes and transportation distances reported by Dones and colleagues (2007) and Sorkka and colleagues (2005, pp. 21).

5.1.3.4 Disposal residues

5.1.3.4.1 Input and output data

The formation of residues from the combustion process has been inventoried based on data reported by Dones and colleagues (2007). Residues resulting from the use of hard coal include hard coal ashes and APC residues from deNOx and desulphurization processes.

The disposal of residues has been modeled assuming that all incineration residues are to be landfilled. In Finland up to 60% of hard coal combustion residues are actually recycled, but the recycling has not been taken into account as it has not been considered for the REF gasification plant either. This will most likely lead to overestimation of environmental impacts, but on the other hand ensures that the inventory is in line with the assumptions made for the gasification plant.

The release of emissions from landfill has been inventoried using the transfer coefficients reported by Doka (2009a) for residual material landfills. The emissions have been calculated over two different time frames: a time frame of 100 years, and an infinite time frame.

5.1.3.4.2 Occupational accidents and commuting accidents

The accidents associated with the disposal of residues have been inventoried based on the standard waste disposal processes described in chapter 5.1.2.4. No stabilization of the incineration residues is assumed to take place.

The occupational and commuting accidents associated with the transportation of residues from the power plant to the landfill have been calculated based on the standard transportation distance reported by Frischknecht and colleagues (2007, pp. 12-14), and the average transportation processes.

5.1.3.5 Deconstruction of the power plant

5.1.3.5.1 Input and output data

Deconstruction of the hard coal power plant has been modeled similarly as the deconstruction of the studied gasification plant. No outputs have however been considered for the emptying of process equipment as all chemicals and other materials are assumed to be suitable for reuse.

The inputs associated with the dismantling have been taken the same as for the gasification plant (i.e. total of 2150 MWh diesel). The outputs from dismantling of power plant and underground structures have been calculated using the emission factors and recycling rates as for the gasification plant. A summary of the material flows is given in table 5.14.

Table 5.14. *Summary of the material flows resulting from the deconstruction*

Construction material	**To recycling**	**To final disposal**	**Dust to air**
Steel [ton]	45850	0	0
Concrete, brickwork, bitumen and ceramics [ton]	148976	0	24[1]
Other materials [ton]	0	611	0

[1]51% PM>10, 39% PM2,5-10, 10% PM<2,5

5.1.3.5.2 Occupational accidents and commuting accidents

Occupational and commuting accidents associated with the deconstruction of hard coal power plant have been calculated similarly as the accidents associated with the deconstruction of the gasification plant. The same working time and accident frequency has been assumed for both plants apart from the working time associated with the emptying of process plant equipment. The working time for the emptying of equipment has been calculated based on the normal operating staff of the studied hard coal power plant similarly as for the gasification plant. The amounts of accidents are given in tables C3 and C12 in appendix C.

5.1.4 Limitations of inventory analysis relative to the goal and scope

The inventory analysis described in this chapter covers all of the processes that have been defined in the goal and scope definition in chapter 3.2. There are however some deficiencies in the coverage of inventory data regarding background processes. For example the infrastructure required for a number of processes has not been considered. Also not all of the recommendations given in chapter 4.4.3 have been followed due to limitations in data availability.

The methodology used for collecting the data is consistent for most parts. Some minor inconsistencies regarding the collection of accident data for the background processes do however exist. For most of the background processes the accidents have been calculated based on aggregated working time data. For some parts aggregated data is not available, and the indirect accidents have therefore been calculated by identifying all linked processes and collecting accident data for them.

The overall data quality level for the inventory data is three or higher indicating that the data is sufficiently reliable to be used for estimating the importance of occupational accidents. The deficiencies in the inventory data do not also conflict the goals and scope of this study, as the study is primarily aimed at determining the practical possibilities of using the proposed methodology for assessing occupational safety. It should be noted that the data quality scores that are given in table 5.15 for each indicator have been determined only qualitatively. Quantitative determination of data quality scores could add some value to the study, and the need for it should be assessed in later studies.

Table 5.15. *Data quality scores for the inventory data (regarding both the input and output data, and accident data)*

Data quality indicator	Score	Description
Technological representativeness (TeR)	2,5	Data regarding the studied marginal technology is collected for all relevant parts. Some deficiencies exist, as parts of the marginal technology have been modeled based on average data.
Geographical representativeness (GR)	3	Inventory data is mainly collected from the geographical area under study. Some deficiencies exist especially regarding the processes taking place in Russia.
Time-related representativeness (TiR)	3	Inventory data is mainly in line with the data quality requirements. Some deficiencies exist in the data collection regarding accident data.
Completeness (C)	2	All identified processes have been covered. Some background processes have not been fully covered, but the deficiencies in the coverage should not have notable impact on the overall results.
Precision / uncertainty (P)	3,5	Literature data regarding average processes has been used to describe some marginal processes. Significant parts of product life cycle have been modeled based on secondary data.
Methodological appropriateness and consistency (M)	1,5	Some small inconsistencies exist in the inventory methods. These should not however affect the outcomes of the study.

5.1.5 Summary of LCI results

The inventory results have been combined using GaBi 5 software based on the product system model illustrated for selected parts in appendix E[18]. The product system model is available for Metso's internal use only, and will not be published as a part of this thesis.

Also the aggregated LCI data regarding both elementary flows to and from the studied product system, and the occupational and commuting accidents will not be published as a part of this thesis. The data is available for Metso's internal use as a part of the product system model.

[18] Appendix E is available for Metso Power's and Metso Corporation's internal use only, and will not be published as a part of the public version of this document.

5.2 Life cycle impact assessment

5.2.1 Guide to characterization factors used

The impacts on human health resulting from the release of emissions have been assessed using the characterization factors used in the Eco-indicator 99 methodology. For this study the egalitarian perspective has been applied as it considers both present and future impacts. **The timeframe has been divided in two parts only based on the release of emissions, not based on the impacts of emission releases.**

The only exceptions to using Eco-indicator 99 characterization factors are the sum parameters of heavy metals to air resulting from waste incineration (Cd+Tl and Sb+As+Pb+Cr+Co+Cu+Mn+Ni+V). The characterization factors for these have been taken as the characterization factor for most harmful component (considering the studied impacts).

The characterization factors for occupational accidents have been taken as those given in chapter 4.5.2 for the specific industry sector and geographical area. The same industry sector is used for determining the characterization factors as has been used for calculating the amounts of accidents (i.e. if for example the accident frequency for NACE2 C has been used for calculating the amount of accidents, the characterization factors for NACE2 C have been used for calculating the impacts on human health resulting from these accidents). In case company specific data has been used, the characterization factor for the specific industry sector which best describes the operation of the company is applied.

5.2.2 LCIA results

LCIA results have been presented separately for two different scenarios. In scenario A the replacement of alternative energy sources – in this case hard coal – is considered. In scenario B no replacement of alternative energy sources is taken into account. The impacts have been reported separately for two time frames (100 years and infinite time frame) and also for two different emission intensities for the gasification plant as discussed in chapter 5.1.1.2.

The detailed LCIA results are given in appendix F for both midpoint and endpoint impacts. A summary of the results is given in figures 5.7 and 5.8 for endpoint impacts only. The results have been given for separate stages of product life cycle divided into groups of processes. The definitions of abbreviations used in figures 5.7 and 5.8 are given in table 5.16. The same abbreviations will be used also in the latter chapters.

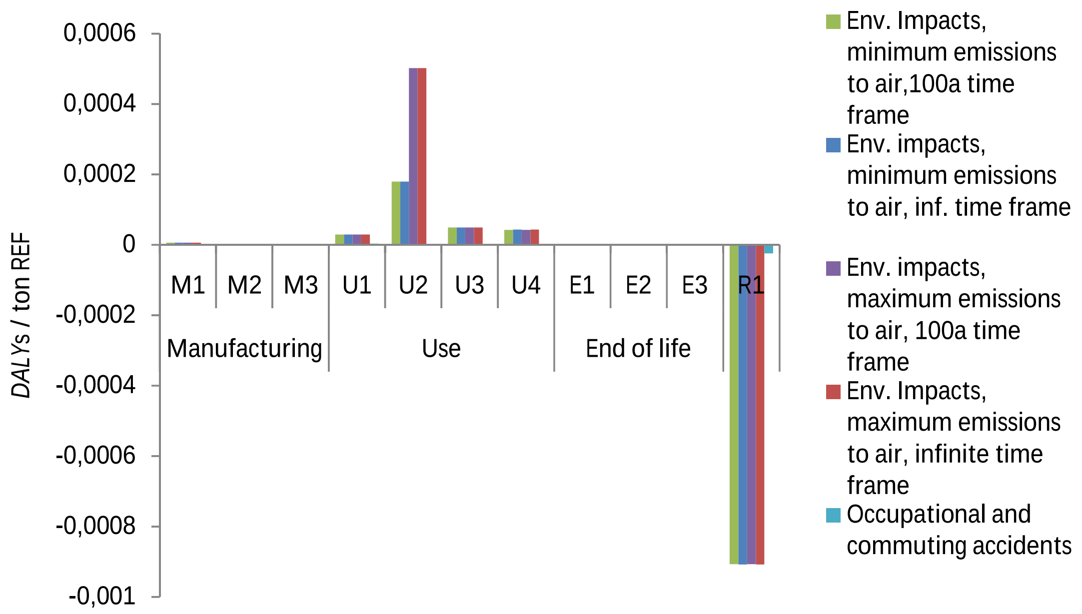

Figure 5.7. *Endpoint LCIA results, scenario A*

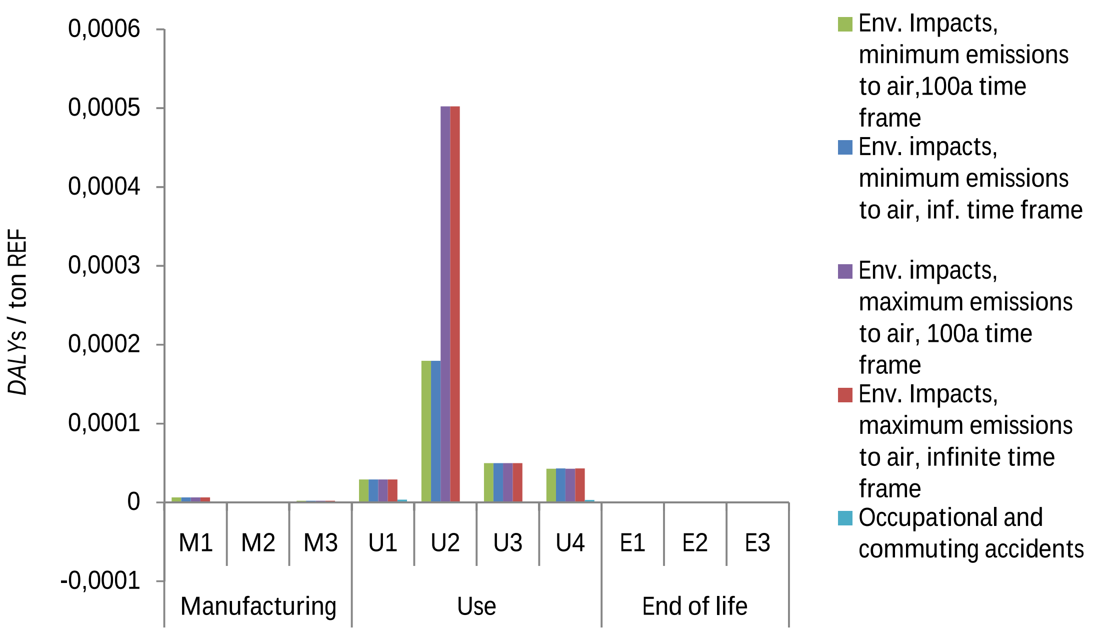

Figure 5.8. *Endpoint LCIA results, scenario B*

__Table 5.16.__ Definitions of abbreviations used in figures 5.7 and 5.8

Abbreviation	Definition	Processes included
M1	Production and transportation of construction materials and energy, and disposal of waste	- Production of construction materials - Transportation of construction materials, train - Transportation of construction materials, truck >32t - Transportation of construction materials, ship - Production of energy (electricity, heat and diesel) for construction processes - Transportation of construction waste, truck 16-32t - Recycling of steel scrap - Disposal of residual construction waste
M2	Premanufacturing of power plant components	- Production of energy (electricity, heat and diesel) - Production of ancillary materials for welding etc. - Premanufacturing of components
M3	Construction of the gasification plant	- Construction of the gasification plant
U1	Production and transportation of REF	- Transportation of separately collected waste to processing plant, truck >32t - Production of REF from separately collected waste - Production of energy (electricity, heat and diesel) for the processing of waste
U2	Operation of the gasification plant	- Operation of the gasification plant
U3	Production and transportation of ancillary materials	- Production of gasifier bed materials - Production of flue gas cleaning chemicals - Transportation of materials, truck >32t - Transportation of materials, train
U4	Transportation and disposal of incineration residues	- Transportation of fly ash, APC residues and bottom ash, truck 16-32t - Stabilization of fly ash and APC residues - Disposal of fly ash and APC residues in residual material landfill - Disposal of bottom ash in slag compartment of sanitary material landfill
E1	Emptying of process equipment	- Emptying of process equipment (excluding the disposal of removed materials)
E2	Deconstruction of the gasification plant	- Mechanical dismantling of the gasification plant - Production of diesel used in the machinery
E3	Transportation and disposal of	- Transportation of waste for recycling or disposal, truck >32t - Recycling of steel and concrete - Disposal of residual waste (including materials removed from process equipment)
R1	Avoided burden from the use of hard coal	- Manufacturing of hard coal power plant - Mining of hard coal - Production and transportation of ancillary materials - Disposal and transportation of incineration residues - Deconstruction of hard coal power plant

6 Interpretation of the case study results

6.1 Midpoint vs. endpoint category indicators

The LCA community is strongly divided when asked whether to use midpoint or endpoint impact assessment methods. The only practical outcome so far is that both methods have their pros and cons, and the best approach is therefore to use them both. This approach was used also in the case study.

The results of this study show that at midpoint level non-fatal accidents are the quantitatively more significant group of accidents; the amount of non-fatal accidents is two orders of magnitude greater than the amount of fatal accidents in both scenarios (see appendix F). When the focus is however shifted to endpoint level, the results reveal that the health impacts resulting from fatal accidents are in fact the same order of magnitude as those originating from non-fatal accidents. This is one vote in favor of using endpoint impact assessment methods: the relative contribution of different types of accidents can be easier understood when assessing the impacts of accidents instead of their number.

The obverse of this is then that using endpoint indicators looses the touch with real life. When occupational safety is measured in cases of accidents, the results are easier to link with real life. Based on the midpoint results can for example be calculated that one life is expected to be lost annually in occupational accidents occurring due to the operation of the plant. This is a much stronger message than the fact that annually some 60 disability adjusted life years are lived due to the operation of the plant. However, using midpoint results in such manner is also a misleading message, as according to the ISO standards, "*LCIA results do not predict [actual] impacts on category endpoints, exceeding thresholds, safety margins or risks*" (ISO 14044). When used in such way, the LCIA results are used in a manner that conflicts the standards.

Another aspect in favor of using an endpoint method is that it enables the comparison of environmental and occupational health impacts. When the environmental and occupational health impacts are measured using same metrics and boundary conditions, possible trade-offs can be identified. This makes it possible to avoid making decisions that improve the environmental performance of products at the cost of their safety.

Finally, the results of this study reveal that using endpoint methods reduces the amount of necessary indicators. If the accidents are assessed at category midpoints, numerous different indicators are needed. It may not even be sufficient to divide the accidents in fatal and non-fatal accidents, as all non-fatal accidents are not equally important considering their impacts on human health. Therefore the non-fatal accidents occurring under different conditions should be further divided into subcategories in order to be able to reflect their impacts on category endpoints. This can easily lead to a group of tens of different indicators making it practically impossible to interpret the results of the study. The endpoint method on the other hand makes it possible to focus on a single metrics only thus making it much easier to interpret the results.

All in all the results of this study indicate that when it comes to occupational health impacts, the endpoint impact assessment methods pose numerous benefits over the midpoint methods. Therefore, and to simplify the interpretation of the results, **the following chapters will focus only on endpoint impact assessment results**.

6.2 Differences between the alternative scenarios

In this paper two different scenarios have been discussed: scenario A, where the system boundaries have been established following the most common guidelines for LCAs of waste incineration system thus including also the compensation for energy production, and scenario B that does not include any compensation resulting from reduced need of hard coal use. Furthermore, the two scenarios include the study of two different time frames (100 year and infinite time frame) and two different emission intensities of the gasification plant, which give the realistic upper and lower limit of direct environmental impacts. All in all, the study therefore includes eight different results which should indicate the realistic upper and lower limits of the human health impacts under the boundary conditions of this study.

The theoretical upper limit of human health impacts for all studied scenarios and boundary settings is obtained in the scenario B with the upper limit emission intensity and infinite time frame, as illustrated in figures 5.7 and 5.8. The lower limit on the other hand is obtained in scenario A with lower limit emission intensity and 100 year time frame. The upper limit for scenario A is obtained with the same boundary conditions as for the scenario B, i.e. by using the upper limit values for direct emissions from the gasification plant and by studying the impacts over infinite time frame. For scenario B the lower limit impacts are then again obtained similarly as for scenario A, i.e. with lower limit emission intensity and by limiting the study to 100 year timeframe only. The difference between short and infinite time frame is however small in all of the studied cases, while the emission intensity has by far greater significance. The impacts on human health in different scenarios are summarized in table 6.1.

Table 6.1. *Impacts on human health in different scenarios (measured in DALYs)*

	Lower limit emissions		Upper limit emissions	
	100 a	Infinite	100a	Infinite
Scenario A: overall health impacts	-6,10E-04	-6,10E-04	-2,87E-04	-2,88E-04
Scenario A: environmental health impacts	-5,98E-04	-5,98E-04	-2,75E-04	-2,76E-04
Scenario A: occupational health impacts	-1,93E-05	-1,93E-05	-1,93E-05	-1,93E-05
Scenario B: overall health impacts	3,25E-04	3,26E-04	6,48E-04	6,48E-04
Scenario B: environmental health impacts	3,09E-04	3,10E-04	6,32E-04	6,32E-04
Scenario B: occupational health impacts	8,59E-06	8,59E-06	8,59E-06	8,59E-06

As can be expected, there is no difference in the occupational health impacts caused by different time frames or emissions intensities. Instead, the emission intensity affects only the environmental health impacts of the plant itself, while the time frame affects mainly the environmental impacts of the disposal of residues. The occupational health impacts differ none the less between the two scenarios. The difference results from the compensation of energy production, which results in reduced occupational health impacts from other energy production routes.

The results of scenario A indicate in all studied cases that the adverse human health impacts of the studied waste gasification plant are negative, i.e. that the plant is actually beneficial regarding human health. This is the result of reduced hard coal consumption, which has greater environmental and occupational impacts on human health than use of REF for energy generation under the boundary conditions of this study.

In order to simplify the interpretation of the results, only the smallest and greatest value in both scenarios will be paid attention to in later chapters. These will provide one with an overview of the range on impacts on human health without complicating the interpretation of results excessively.

6.3 Contribution of accidents to human health impacts

Based on the LCIA results given in appendix F and figures 5.7 and 5.8 in chapter 5.2.2, the occupational accidents are not the leading cause of human health impacts at least in the studied case. Instead, depending on the emission intensity and studied time frame, some 95-99% of the human health impacts are caused by the release of emissions to air and water.

Occupational and commuting accidents are none the less a significant contributor to the human health impacts. For some processes occupational and commuting accidents are even the leading cause of human health impacts. For instance, 60% of the direct impacts on human health resulting from the pre-manufacturing of power plant components are caused by occupational and commuting accidents. There are on the other hand also opposite examples as can be seen in figure 6.1. The occupational and commuting accidents for example account for less than 0,2% of all human health impacts resulting from the operation of the gasification plant.

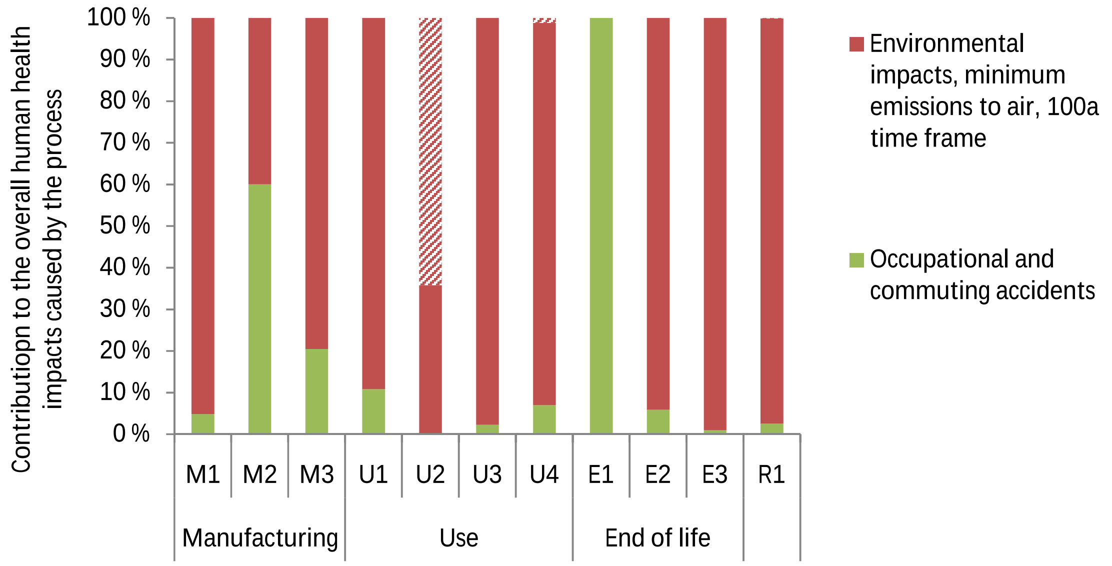

Figure 6.1. *Contribution of occupational and commuting accidents to the human health impacts caused by different processes. The striped area of environmental impacts indicates the difference between minimum and maximum impacts. The definitions of abbreviations used are given in table 5.17 in chapter 5.2.2.*

The occupational accidents have notably greater contribution to the human health impacts than the commuting accidents: 93% of all occupational health impacts in scenario A and 87% in scenario B are caused by occupational accidents. Still, also the commuting accidents have a notable contribution to the human health impacts. In scenario A the majority of health impacts of occupational accidents are caused by fatal accidents, while in scenario B the majority of health impacts originates from non-fatal accidents. In the case of commuting accidents the fatal accidents have greater contribution to the human health impacts in both scenarios. The contribution of different types of accidents to the occupational health impacts is shown in figures 6.2 (scenario A) and 6.3 (scenario B).

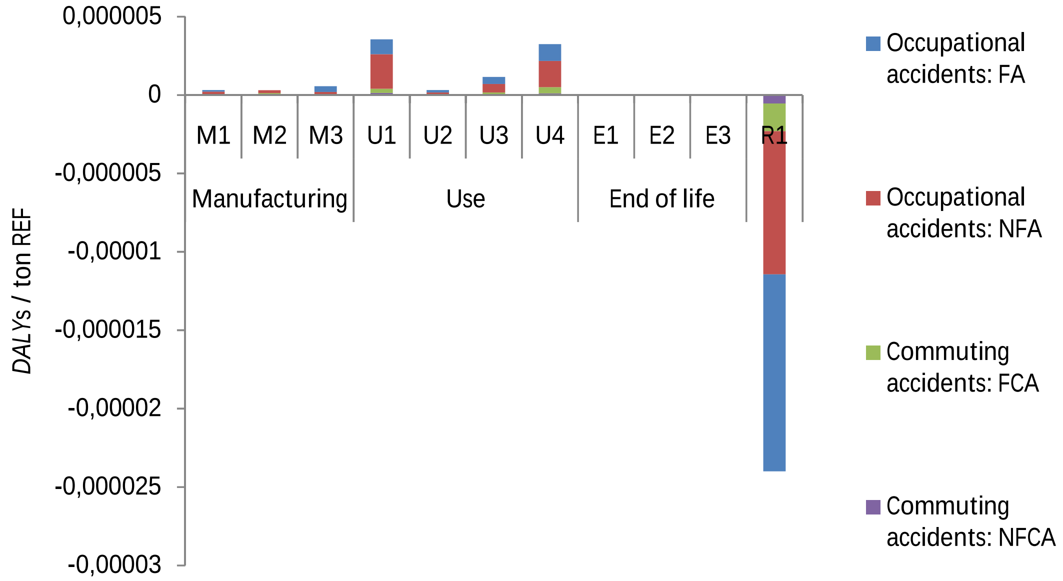

Figure 6.2. *Breakdown of occupational health impacts by the type of accident and group of processes in scenario A. The definitions of abbreviations used are given in table 5.17 in chapter 5.2.2.*

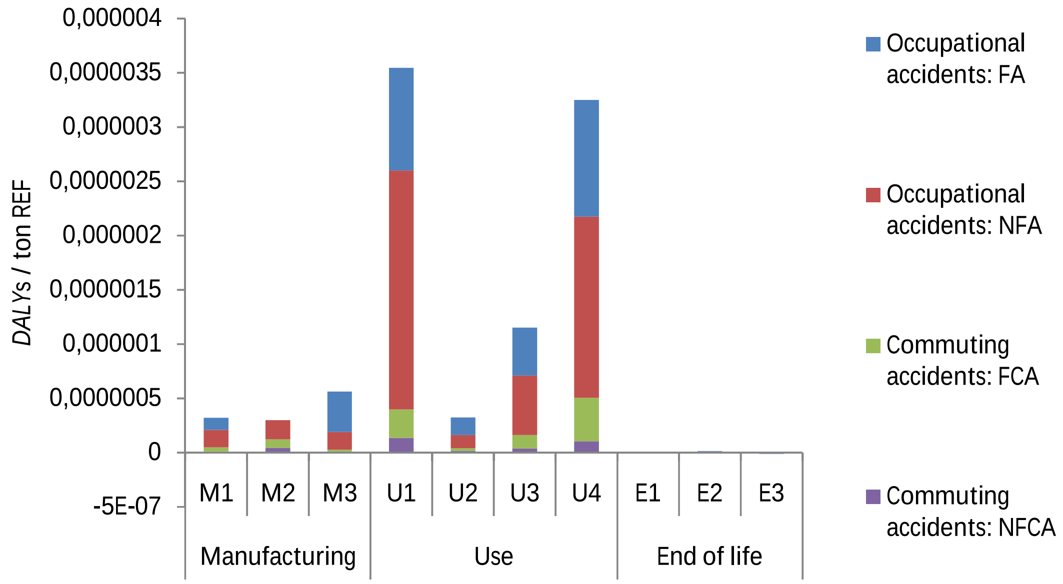

Figure 6.3. *Breakdown of occupational health impacts by the type of accident and group of processes in scenario B. The definitions of abbreviations used are given in table 5.17 in chapter 5.2.2.*

A vast majority of the human health impacts happen to other than Metso's or its subcontractors' employees. Also the power plant operator's employees account for a somewhat small share of all occupational and commuting accidents. Instead, the individual group of employees with the greatest contribution to the occupational health impacts is the people involved in the processing of REF.

6.4 Differences between hotspots

Depending on the studied scenario, the majority of both environmental and occupational health impacts result from either the use stage or the compensation from avoided energy production. In both cases the adverse impacts originate mainly from the use stage of the studied plant. In case the replacement of alternative energy sources is considered (scenario A), the reduced consumption of hard coal and the compensation from it is the ruling factor for both environmental and human health impacts. The environmental health impacts of hard coal originate mainly from the mining and combustion of hard coal (30,8% and 59,2% of environmental health impacts), while the occupational health impacts originate almost explicitly from the mining and transportation of hard coal.

In scenario B the majority of the (adverse) environmental human health impacts result in from the combustion process (58-78% depending on emission intensity and time frame). Also the production of materials and disposal of incineration residues have a notable contribution to the environmental health impacts (7-14%). The production of REF accounts for some 5-8% of the environmental health impacts, with the share of transportation being roughly half of this. The construction of power plant and manufacturing of materials needed for it accounts in all cases for less than 3%, and the deconstruction for less than 1% of the environmental health impacts.

In scenario B the human health impacts resulting from occupational and commuting accidents on the other hand are primarily caused by the processing of REF (39%). The second greatest contributor is the disposal of incineration residues (36%), and the third greatest the production of flue gas cleaning chemicals (13%). The accidents associated with the production of REF take mainly place in the production site. The operation of the power plant itself is among the smallest contributors falling just above the pre-manufacturing of power plant components. All in all, the use stage accounts for some 92% of the human health impacts resulting from occupational and commuting accidents in scenario B.

Comparing the hotspots of environmental health impacts and health impacts caused by occupational and commuting accidents reveals that although the big picture is quite similar, there are still some distinct differences. Whereas the operation of the power plant is the biggest sole contributor to the environmental health impacts, it is actually among the smallest contributor considering health impacts of occupational and commuting accidents. Instead, the occupational health impacts result mainly from the disposal of incineration residues and production of REF and flue gas cleaning chemicals. Also other notable differences occur, as can be seen from figures 6.4 and 6.5.

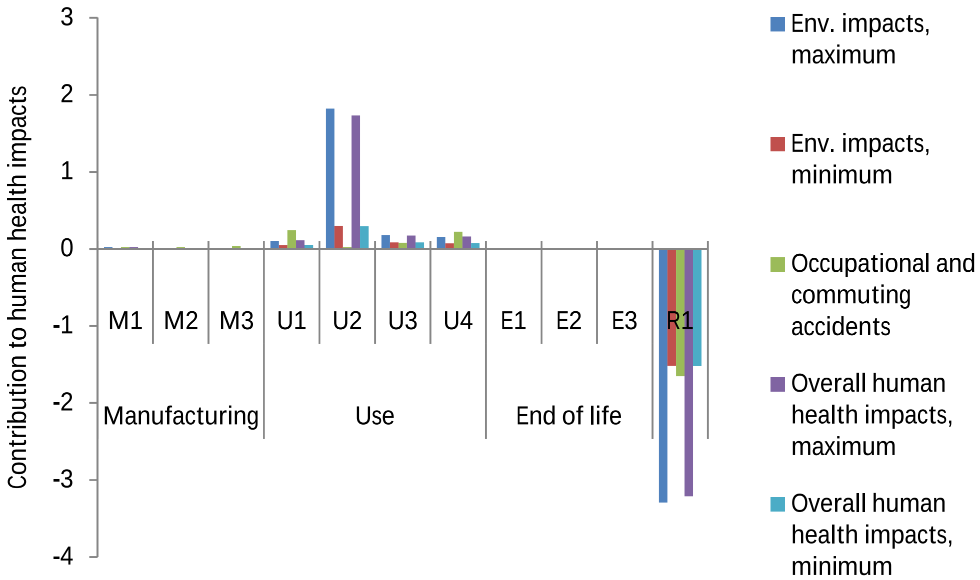

Figure 6.4. *Relative contribution of different processes to the overall human health impacts, environmental health impacts and occupational health impacts in scenario A. The definitions of abbreviations used are given in table 5.17 in chapter 5.2.2.*

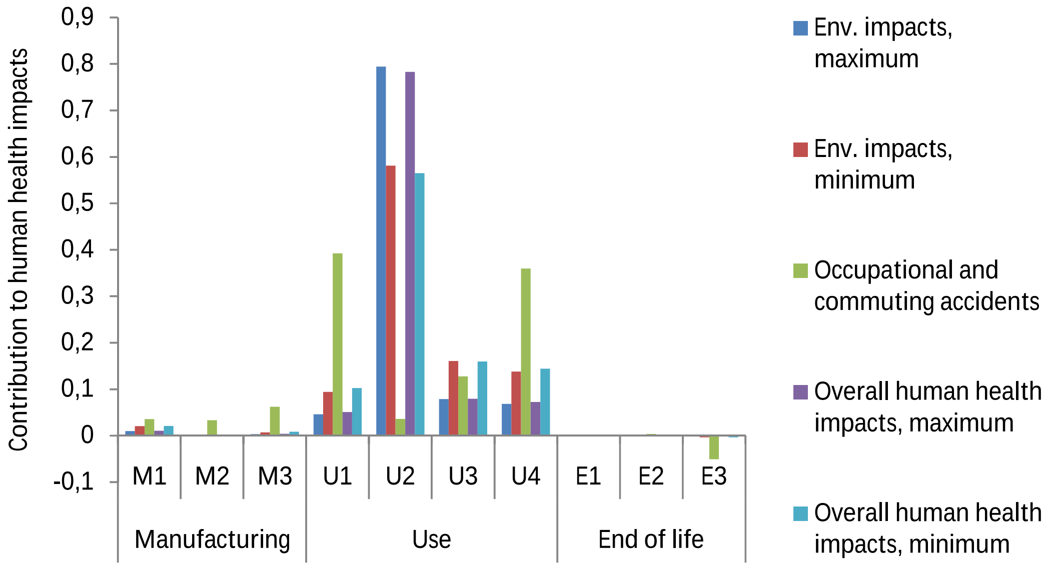

Figure 6.5. *Relative contribution of different processes to the overall human health impacts, environmental health impacts and occupational health impacts in scenario B. The definitions of abbreviations used are given in table 5.17 in chapter 5.2.2.*

The purpose of LCA studies is often to identify the relatively most harmful parts of the product life cycle. The comparisons illustrated in figures 6.4 and 6.5 show that the relatively most harmful processes considering the environmental impacts are not necessarily the most harmful considering occupational health. Therefore trying to avoid environmentally harmful processes does not necessarily lead to reduced occupational health impacts.

Judging by the difference in environmental hotspots and those of occupational safety, there is an apparent risk for trade-offs in case decisions are made purely based on LCA results. As the majority of environmental health impacts results from the operation of the power plant, the way to reduce them is to further reduce the amount of harmful substances in the flue gas. This on the other hand leads to increased need for the disposal of incineration residues and is also likely to increase the consumption of flue gas cleaning chemicals. Both the increased consumption of chemicals and the increased production of incineration residues on the other hand risk increasing the occupational health impacts. The emissions could also be reduced by using higher quality REF. The further processing of REF then again is known to increase the risk of occupational accidents (European Commission 2006).

The inclusion of occupational safety in LCA can help highlight the possibility of trade-offs between environmental impacts and occupational safety. Some of the trade-offs are already known (e.g. European Commission 2006), but the lack of quantitative data may still hinder their effective management as argued by Hendrickson and colleagues (2006). Here LCA can be of great use.

6.5 Role of other than occupational accidents

This case study has demonstrated that although occupational accidents are not the leading cause of human health impacts, it is essential that they are taken as a decision making criteria even in LCA studies. This is in fact in line with the general view and impacts of occupational safety: on a global scale occupational accidents are not the leading cause of fatalities or other human health impacts, but they are still a crucial aspect of corporate responsibility (Concha-Barrientos et al. 2005). In fact, occupational accidents are not even the leading cause of human health impacts resulting from different types of accidents (Concha-Barrientos et al. 2005). Therefore the question emerges that what is the role of accidents causing damage to other than workers considering the human health impacts and foremost the possible decisions made based on LCA derived information. The purpose of this chapter is to create a rough overview of the potential human health impacts experienced by other than workers. The primary aim is not to develop detailed information to support the evaluation of these impacts, but rather to identify any needs for further studies.

In order to identify the possible role of other accidents than occupational and commuting accidents, one has to first identify what types of accidents the studied product system may account for and who are the victims of these accidents. The accidents can be divided in two categories on a very upper level: **natural disasters** and **technological accidents**. The first category is affected indirectly through for example the release of GHG emissions which then increase the risk for flooding and other natural disasters (Pennington et al. 2004). These impacts are covered through several environmental impact assessment methods – including the one used in the case study – and are therefore accounted for (Goedkoop & Spriensma 2001). The technological accidents then again are only partially covered. Accidents leading to damages on environment and then indirectly contributing to natural disasters have to some degree been included in this study. The direct impacts on human health are also included, but only to the degree they affect the workers. Any bystanders are not considered here, which implies that there may be room for improvement or at least a reason to check if the omission of damages to bystanders may contort the recommendations made based on the case study.

In order to further study the impacts of technological accidents, one has to know the damage caused to bystanders by different types of accidents. Here the classification presented by the National Occupational Health and Safety Commission of Australia (1998) is applied, and bystanders are divided in two groups:

1. **Workplace bystanders**: people not working who were injured as a result of workplace activities not associated with public roads or public transport
2. **Road bystanders**: people not working who were injured in motor vehicle accidents on a public road (or public transport) as a result of other people's work.

The accidents resulting in damages to these two categories of bystanders are evaluated here. The evaluation is focused on incidents causing limited damages only. No extensive industrial accidents such as explosions of industrial facilities have been considered here.

6.5.1 Accidents to workplace bystanders

There is very little published data regarding the amount of workplace bystanders killed or injured in technological accidents. According to a study in Australia, for every 100 workers killed in occupational accidents some 17 workplace bystanders are killed (National Occupational Health and Safety Commission 1998). In addition, some 300 bystanders were estimated to be injured for every one dead bystander in the USA in early 90s (Leigh et al. 2000). Most risky industry sectors for bystanders in Australia are transportation and storage, and electricity, gas and water supply, where 41 and 18 bystanders were killed for every 100 fatally injured workers in 2005-2009 (including also road bystanders) (National Occupational Health and Safety Commission 2008; 2009a; 2009b). Most of the bystanders killed in the field of transportation and storage are on the other hand probably road bystanders, whereas workplace bystanders are mainly killed in other industry sectors. Furthermore, the amount of bystanders that are reported to be killed in technological accidents is probably underestimated indicating that the actual amount of bystander fatalities may be even greater (National Occupational Health and Safety Commission 2008; 2009a; 2009b).

For this study a rough estimate of the human health impacts resulting from damages to workplace bystanders as a result of technological accidents is made based on data reported for Australia. A summary of the bystanders killed in technological accidents in different industry sectors is given in table 6.2 for Australia. All of the bystanders killed in the field of transportation and storage have been assumed to be killed in road traffic accidents and are therefore not considered in table 6.2. The fatalities in all other industry sectors have been taken as workplace bystanders, which is probably a misinterpretation for two reasons. First of all, some of the bystanders may actually be road bystanders that are killed in accidents occurring during business travelling. Secondly, some of the bystanders are workers. Still, given the fact that the amount of bystander fatalities is underreported, this can be used for estimating their amount at a very rough level.

Table 6.2. *Amount of bystanders killed in technological accidents in Australia in 2005-2009. The values have been given as the amount of bystander fatalities for every 100 fatally injured workers. (National Occupational Health and Safety Commission 2008; 2009a; 2009b)*

Industry sector	2005	2006	2007	2008	Average
NACE2 A	7	5	n.d	2	5
NACE2 B	0	7	n.d	0	2
NACE2 C	4	0	n.d	0	2
NACE2 D	0	67	n.d	0	18
NACE2 E	n.d	n.d	n.d	n.d	n.d
NACE2 F	5	0	n.d	13	5
NACE2 H	0	0	n.d	0	0

The bystander accidents in NACE2 E sector have been approximated based on data for NACE A-F and H average (2,8 bystander fatalities for every 100 worker fatalities). NACE A-F and H average has been calculated using equation (13), but excluding NACE2 E from the calculation. Also, accident frequency used in equation (13) is in this case replaced with the ratio of bystander fatalities and worker fatalities reported in table 6.2. The amount of non-fatal bystander injuries has been taken as 300 times the amount of fatal bystander injuries.

The characterization factor for non-fatal injuries is taken as that for non-fatal occupational accidents in EU-15 area. The characterization factor for fatal injuries is taken as 45,8. The characterization factor is calculated based on age and sex distribution of bystanders killed in technological accidents in Australia in 2006 because no detailed data is available for other years and/or regions, and the average life expectancies reported for the population of the specific age in Europe using equation (6).

The amounts of bystanders killed and injured in technological accidents over the life cycle of the studied product system can be determined by multiplying the amounts of occupational accidents associated with the studied product system in different industry sectors with the factors given in table 6.2. This results in the amount of bystander accidents listed in appendix G (table G1) for different stages of product life cycle. The human health impacts can then be calculated by multiplying the amounts of non-fatal and fatal bystander accidents with the respective characterization factors. The weighted values are given in appendix G as well.

6.5.2 Accidents to road bystanders

The accidents to road bystanders occur mainly when vehicles used for transportations collide with other vehicles or pedestrians. Also commuting accidents account for some accidents to road bystanders. In Australia the amount of road bystanders killed in accidents is about the same magnitude as the amount of workplace bystanders killed in accidents (National Occupational Health and Safety Commission 1998). On the other hand, in Finland the road traffic accidents involving trucks used for goods transportations are reported to account for over 90 fatal accidents annually, which is notably more than the amount of truck drivers killed in occupational accidents (Ministry of Transport and Communications 2010). Some 20 people are also killed annually in railway accidents (Accident Investigation Board 2007). Furthermore, commuting accidents can often result in the death of road bystanders even if the commuters themselves are not killed in the accidents. Some 65% of all people killed in commuting accidents are killed onboard passenger cars (Luoma 2011). On average, 100 fatalities in passenger cars account for 28 bystander fatalities (Peltola & Aittoniemi 2008).

When calculating the amount of road bystanders first the decision has to be made whether or not injured and killed bystanders include only those that have been killed or injured in accidents that are caused by the workers or parts of product system involved in them. The National Occupational Health and Safety Commission of Australia defines road bystanders as the people that have been killed in accidents *“where the working vehicle was primarily ‘at fault’ in the incident”* (National Occupational Health and Safety Commission 1998). In Finland for instance a majority of the fatal accidents including trucks are caused by other road users (Vehmas et al. 2009). Fatal road traffic accidents even involve a number of cases, where the accident has been caused on purpose in order to commit a suicide.

The exclusion of accidents where the working vehicle has not been at fault would still be value choice indicating that the operation of the working vehicle does not contribute to the accident in any way. This would also imply that increased traffic flows would not increase the risks of traffic accidents. Differing opinions have been presented whether or not this holds true. Here all accidents have been included independent of if the working vehicle has or has not been at fault in order to get an overview of the maximum amount of bystander casualties. The only accidents that have been excluded are those that have been caused on purpose, as it is obvious that the magnitude of traffic flow does not affect their relevance. Also the accidents where the bystander is a commuter or travelling on a business trip have to be excluded to avoid double counting.

For this study the amount of road bystanders killed in accidents has been taken as those given in table 6.3. The bystander accidents have been considered only for road and railway transportations and commuting accidents, as they have been assumed to be the primary contributors to road bystander injuries and fatalities. 16% of road bystanders in road traffic accidents involving trucks and 5,5% of road bystanders in railway accidents have been excluded from the calculation because the accidents have been caused on purpose (Vehmas et al. 2009; Accident Investigation Board 2007). In addition, 2% of all the people killed and 3% of all people injured in road traffic accidents and railway accidents have been assumed as commuters in the NACE2 A-F and H sectors and have therefore been excluded from the calculations[19].

Table 6.3. *Amounts of road bystanders killed due to different modes of transportation and commuting*

Mode of transportation	**FA**	**NFA**	**Comments and references**
Truck transportations [1/tkm]	3,22E-09	1,95E-08	Calculated based on Ministry of Transport and Communications (2010), Vehmas et al. (2009) and data regarding accidents associated with truck transportations
Rail transportations [1/tkm]	7,03E-10	3,97E-09	Calculated based on Accident Investigation Board (2007) and Finnish Transport Agency (2011).
Commuting accidents [1/fatal commuting accident]	0,271	n.d	Calculated based on Luoma (2011) and Peltola & Aittoniemi (2008). No data is available regarding the bystanders injured due to commuting accidents, and they have therefore not been considered here.

[19] It has been estimated that 6% of all workers killed in commuting accidents were working in NACE2 A-F and H sectors. This has been calculated based on data reported for all commuting accidents by the Federation of Accident Insurance Institutions (2011). Workers killed in road traffic accidents during the course of work have not been considered here, as their share is considered negligible and furthermore as it is hard to identify which of them were covered by the NACE2 A-F and H sectors.

The amounts of bystanders killed and injured have been calculated based on data reported for Finland, and does not therefore accurately describe the situation in other countries. But as the purpose here is again to merely study the magnitude of human health impacts resulting from bystanders being injured or killed, the Finnish data has been considered to be suitable to create a rough overview of the issue. A summary of road bystanders killed or injured in accidents associated with the studied product system is given in tables G2 and G3 in appendix G.

The characterization factors for bystanders injured in different traffic accidents is taken as the characterization factor for commuting accidents in Finland area. The characterization factor for fatal accidents is taken as 36,8. The characterization factor is calculated based on age and sex distribution of bystanders killed in traffic accidents in Finland (as reported by Peltola & Aittoniemi (2008)), and the average life expectancies reported for the population of the specific age and sex in Finland using equation (6). The weighted values for damages experienced by road bystanders (i.e. impacts on human health) are given in table appendix G (tables G2 and G3) as well.

6.5.3 Summary of human health impacts on bystanders

The first thing to note when drawing together the information presented in the previous two chapters is that it is merely indicative data. The amounts of human health impacts on bystanders have been calculated based on data that has in many cases poor time-related and geographical representativeness. The data is for most parts also very uncertain, and there is a notable risk of double counting some of the impacts (e.g. workers killed or injured during business trips have not been excluded from the calculations). Still, even considering these limitations one can notice that the damages to bystanders do have a notable impact on the outcomes of this study, as illustrated in figures 6.6 and 6.7.

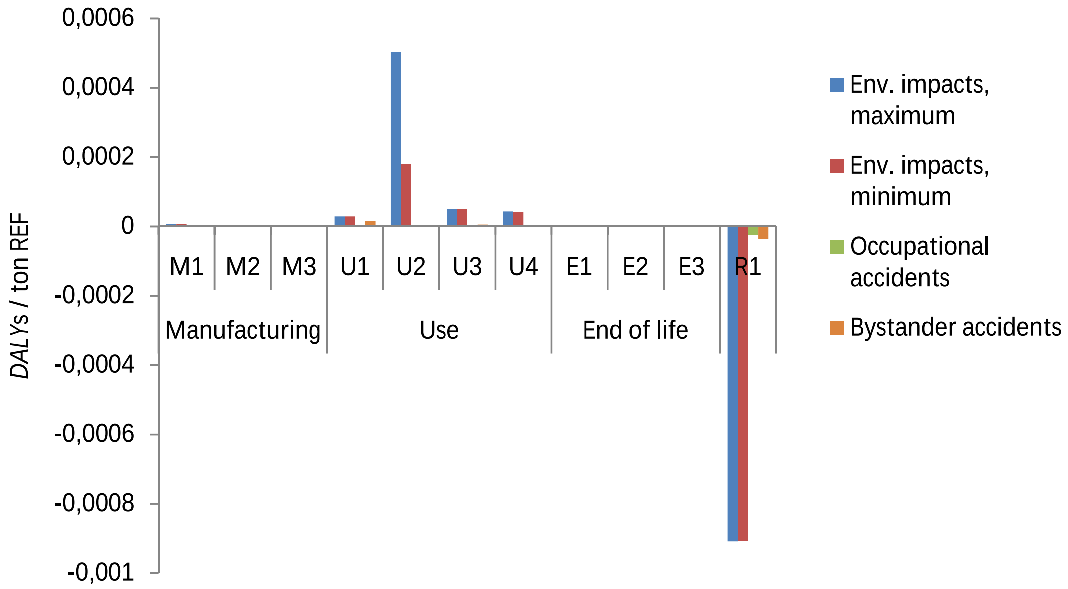

Figure 6.6. *Human health impacts caused by damages to bystanders in scenario A. The definitions of abbreviations used are given in table 5.17 in chapter 5.2.2.*

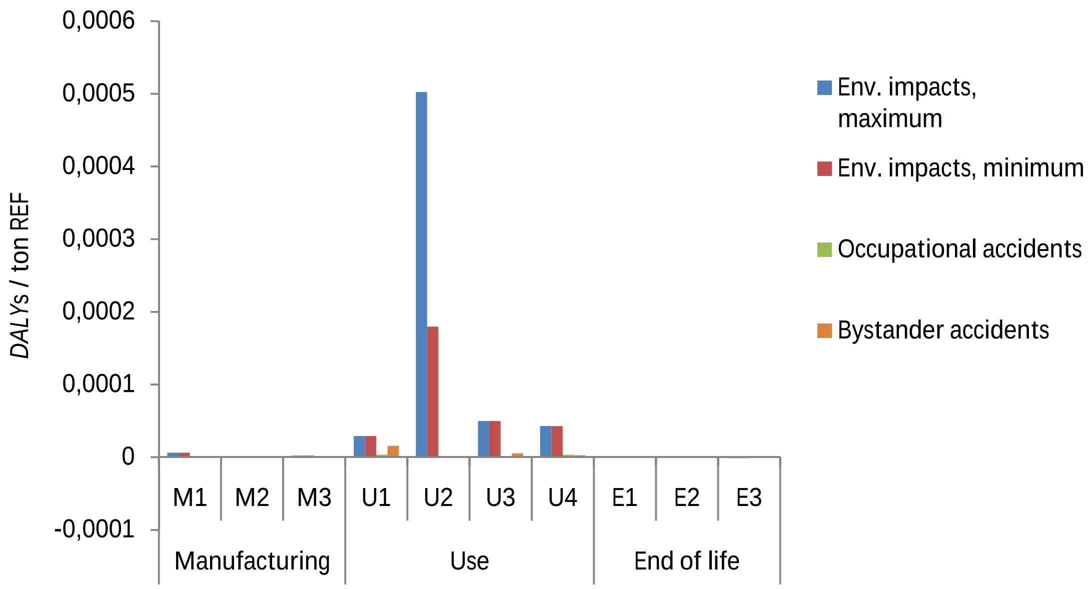

Figure 6.7. *Human health impacts caused by damages to bystanders in scenario B. The definitions of abbreviations used are given in table 5.17 in chapter 5.2.2.*

When comparing the damages to bystanders' health with the damages to workers' health one can observe that the damages experienced by bystanders are notably greater than those experienced by workers. The majority of the impacts result from traffic accidents and more precisely from the transportation of waste to REF production facility. The damages to road bystanders account for over 99% of all damages to bystanders, while the damages to workplace bystanders account for less than 0,1% of all damages to bystanders. The damages to workplace bystanders are also three orders of magnitude smaller than the damages to workers' health resulting from occupational accidents.

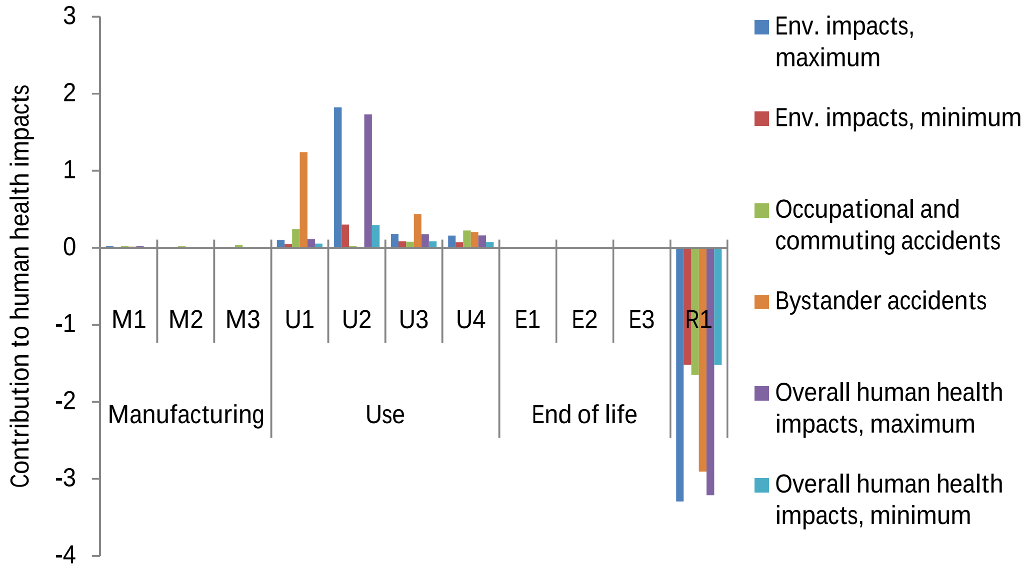

Figure 6.8. *Relative contribution of different processes to the human health impacts in scenario A. The definitions of abbreviations used are given in table 5.17 in chapter 5.2.2.*

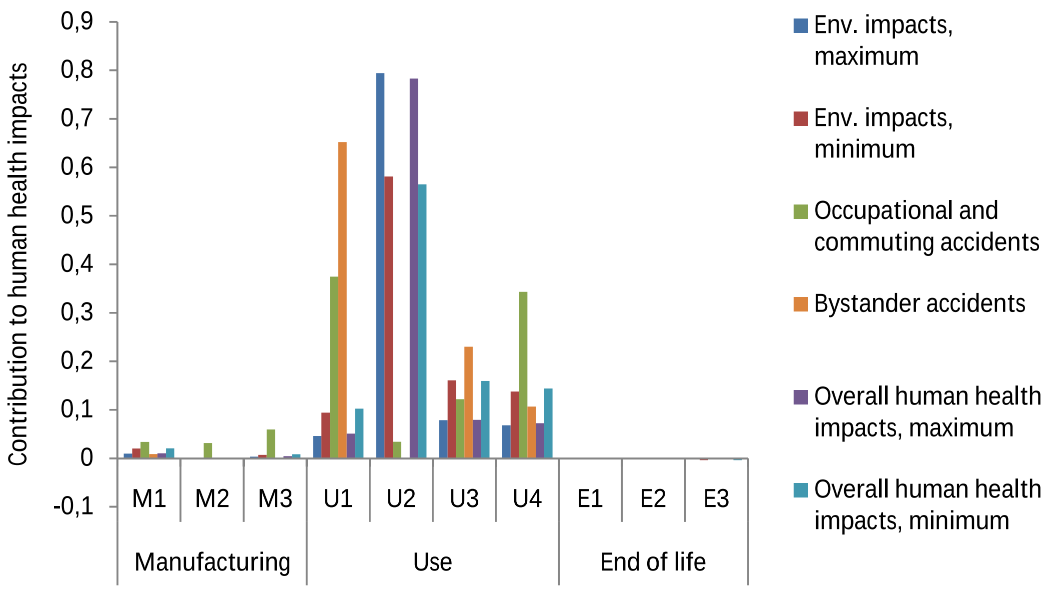

Figure 6.9. *Relative contribution of different processes to the human health impacts in scenario B. The definitions of abbreviations used are given in table 5.17 in chapter 5.2.2.*

There are again notable differences between the hotspots regarding environmental and occupational health impacts, and impacts on bystanders' health, as can be seen in figures 6.8 and 6.9. The differences in the hotspots cause the system to be exposed to possible trade-offs. Also some similarities exist, as the use stage is the leading source of human health impacts in all three categories.

The production and transportation of REF is the leading cause of both occupational and bystander accidents. In the case of occupational accidents the majority of impacts is however caused by the production process itself, while the bystander accidents are mainly caused by the transportation of REF. There is therefore a possibility of trade-offs even within the specific group of processes: while the more centralized processing of REF could possibly lead to a decrease in occupational health impacts (as the process becomes economically more feasible to automate), it could in the same time cause the transportation distances to be increased. This could then lead to increased impacts on bystanders' health.

6.6 Sensitivity of the results

The sensitivity of results is an important factor regarding decision making. In case the results are easily affected by variation in the inventory data, assumptions regarding background technologies or other sources of variation, the decisions made based on the data can be biased. It is therefore important to know the degree to which different sources of variation affect the results.

In the case study a major share of health impacts are caused by a handful of processes. These are in many cases background processes or the compensation from avoided use of hard coal and therefore subject to a variety of assumptions. In fact, the accidents that can even theoretically be measured (i.e. they have taken place by the time the study is carried out) account for only little over 10% of all the occupational health impacts. The majority of occupational health impacts have therefore been calculated based on estimated data and can as a result cause bias in the overall results.

First of all, the avoided burden from hard coal can be overestimated in case the avoided burden comes from plants that would be built instead of the existing plant, or from plants that would be built in the future. In such cases the emissions of heavy metals to air could be up to three orders of magnitude smaller and the emissions of NOx, SO_2 and dust could be up to 50% smaller than what is assumed for this study (Bauer et al. 2008; Bauer 2008). Although the uncertainty caused by this assumption is notable, it does not affect the overall outcome for the part that the avoided burden is actually greater than the adverse impacts caused by the gasification plant. It also does not notably change the relation of occupational and environmental health impacts.

Another significant source of uncertainty considering the environmental health impacts is the uncertainty of the gasification plant's emission intensity. In this study the minimum and maximum values were determined based on the possible range of emissions. Although the difference between the minimum and maximum is notable, it again does not affect the outcome of this study. The avoided burden from hard coal use still remains greater than the adverse impacts caused by the gasification plant, and the environmental health impacts are notably greater than the occupational health impacts in any case.

The uncertainties regarding the occupational health are caused by a variety of factors. First of all the working time assumed for different processes may differ from what is assumed for this study. Secondly, the accident frequency may be different. Finally, the type of background process may be different to what is assumed here. Both variations in the working time and accident frequency are directly proportional to the occupational health impacts. As a major share of occupational health impacts is caused by a few processes alone, the variations in the occupational health impacts caused by them can have a notable effect on the overall results. To study whether or not this is the case, the effects of variation in the working times and accident frequencies of the two most significant processes are demonstrated in figures 6.10 and 6.11. The sensitivity analysis illustrated in figures 6.10 and 6.11 is not intended to provide one with limits of error of any kind, but to rather provide a quick overview of the sensitivity of the results.

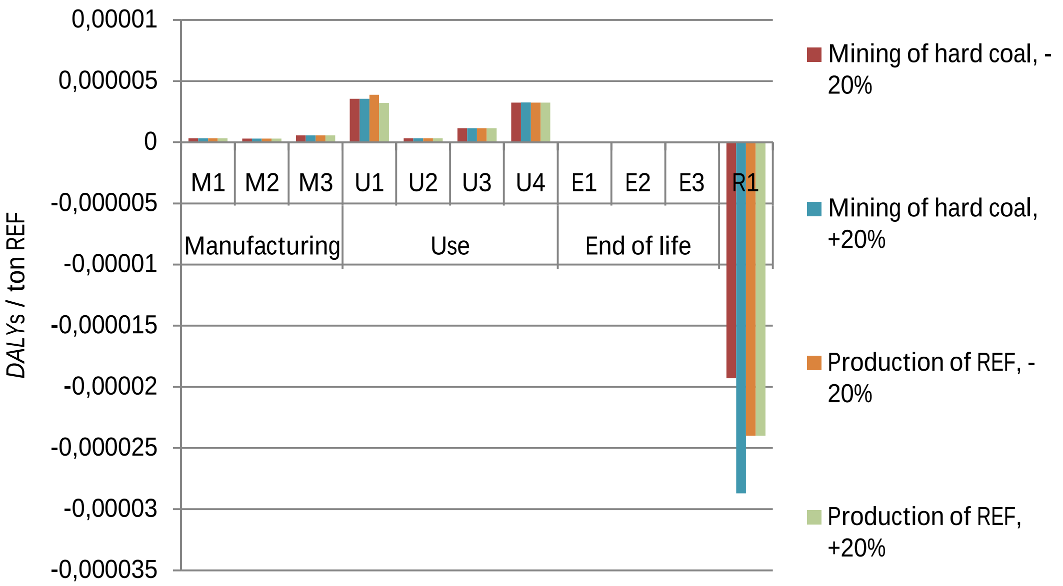

Figure 6.10. *Impacts of variation in working time or accident frequency of selected individual processes on occupational health impacts, scenario A. Red bars mark the reference level for all process groups. The definitions of abbreviations used are given in table 5.17 in chapter 5.2.2.*

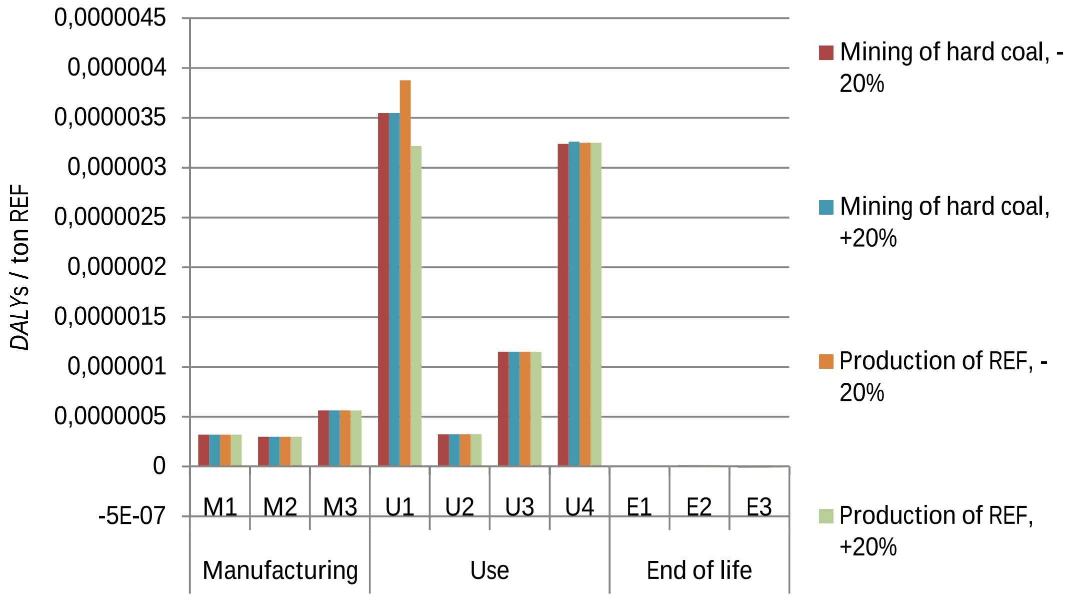

Figure 6.11. *Impacts of variation in working time or accident frequency of selected individual processes on occupational health impacts, scenario B. Red bars mark the reference level for all process groups. The definitions of abbreviations used are given in table 5.17 in chapter 5.2.2.*

Based on the results given in above figures, it can be concluded that modest variations in the working time or accident frequency of individual process is not likely to cause major changes in the relative importance of processes. This holds true even for processes with high relative significance. Still, the deviations in inventory data can cause notable changes in the LCIA results regarding individual processes.

Another source of uncertainty is the assumptions regarding background technologies. If in the studied case for example all electricity needed for example for the production of REF, which is the biggest sole consumer of electricity, was produced from hard coal, the occupational health impacts of the specific process would be increased by ca. 6%, and the overall occupational health impacts by ca. 2%. The difference is not overwhelming, but can in some cases be enough to change the ranking of processes.

All in all, it can be concluded that small uncertainties in the inventory data are not likely to cause notable error in the results. However, the fact that major share of the impacts arise from background processes which are known to pose great uncertainty in the data (at least regarding their environmental impacts). Therefore even greater variations as studied here can occur. This makes it that the uncertainty analysis of the results of the study is essential for any future study.

6.7 Applicability of LCI and LCIA methods

6.7.1 Applicability of different data collection approaches

A number of different data collection approaches were used in the case study. Above all the working times associated with the production of specific goods were determined through numerous different approaches. In many cases the working time was determined by dividing the overall working time associated with the production of a good in a reference area by the overall production value. In some cases the working time was obtained directly from literature for a specific process, and in some cases it was obtained through personal communications.

The separate approaches were of different laboriousness and are likely to pose different uncertainties. All in all, the approach of estimating the working time based on national overall values was probably the easiest approach given that the necessary data was available. This approach is in fact nothing new in the field of LCA: the input-output models have commonly been used for collecting data for life cycle inventories. The drawback of the method is however that it accounts for notable loss of data: the approach is only suited for collecting aggregated average data (Curran 2006). In case data regarding individual processes or working tasks is required, the approach cannot be used. In other cases it offers one an easy first estimate of the working time.

The preparation of input-output models also requires a lot of work and statistical professionalism (Schmidt et al. 2004). In this study the input-output approach is used only if readily collected data has been available. The collection of further data is recommended to simplify any additional studies, but it should be carried out as a separate task.

Another difficulty with using the method is that it provides only limited information regarding the indirect accidents, which in most cases are the leading cause of occupational health impacts (Hofstetter & Norris 2003). Two different approaches were used to cope with this problem: the indirect accidents were either inventoried by compiling data regarding the processes that are causing the indirect accidents, or by using data of indirect working time reported for the specific good. The advantage of the first approach is that it enables a more detailed study of the system. On the other hand, it also requires a lot of additional data further complicating the study. It is also likely that not all processes can be covered. The approach of using indirect working time on the other hand looses all details and makes it impossible to study the impacts of different processes in greater detail. It is also exposed to value choices as it can be unclear where to draw the line with indirect working time. Should for example the work done by taxi drivers when carrying business men be allocated to a production of specific good as indirect working time?

The first approach can be assumed to account for underestimating the actual working time, but the latter can just as well be considered to result in overestimations. Still, as the latter approach is notably less laborious, it is recommended to be used as the primary method. The method of compiling data about all linked processes should be used only if the studied good delivered by the system is of notable interest, or if no estimates regarding the indirect working time are available.

Collecting the data for a specific process from literature or through personal communications can provide one with accurate data regarding the studied process. The drawback is however again the fact that it can rapidly increase the laboriousness of the study. Also, if data collected for a specific type of production process is used to represent the production of a given good, any changes in the applied technology can have notable impact on the working time and also accident frequency. An easy example of this is the production of energy: if for example data collected specifically for the production of energy from peat is used to represent all energy production, changes in the energy production method can have notable impact on the outcomes of the study. Therefore data collected specifically for a given type of process should be used only for the process itself, and not be used to represent any average case or other processes providing the same good or service.

In any case a further study of the possibilities of providing accurate and precise information using different data collection approaches is needed. This has not been done as a part of this thesis as it is not in the scope of this study to evaluate different data collection procedures.

6.7.2 Use of industry and area specific characterization factors

In this study characterization factors for non-fatal accidents were defined specifically for each industry sector. Also different characterization factors were used for different geographical areas (although in this study only two areas were studied separately). All of this was done to ensure that no unnecessary loss of information would occur. Whether or not this is necessary was left an open assumption and therefore needs to be reviewed.

To study whether or not the industry and region specific characterization factors are required, a comparison between the human health impacts calculated using both industry and case specific characterization factors, and impacts calculated using average characterization factors is carried out. For this comparison the average characterization factor for fatal occupational and commuting accidents is taken as the characterization factor for fatal occupational accidents in EU-15 area. For non-fatal accidents the characterization factor is takes as that for NACE A-F and H average in EU-15 area. The results of the comparison are presented in figures 6.11 and 6.12 below.

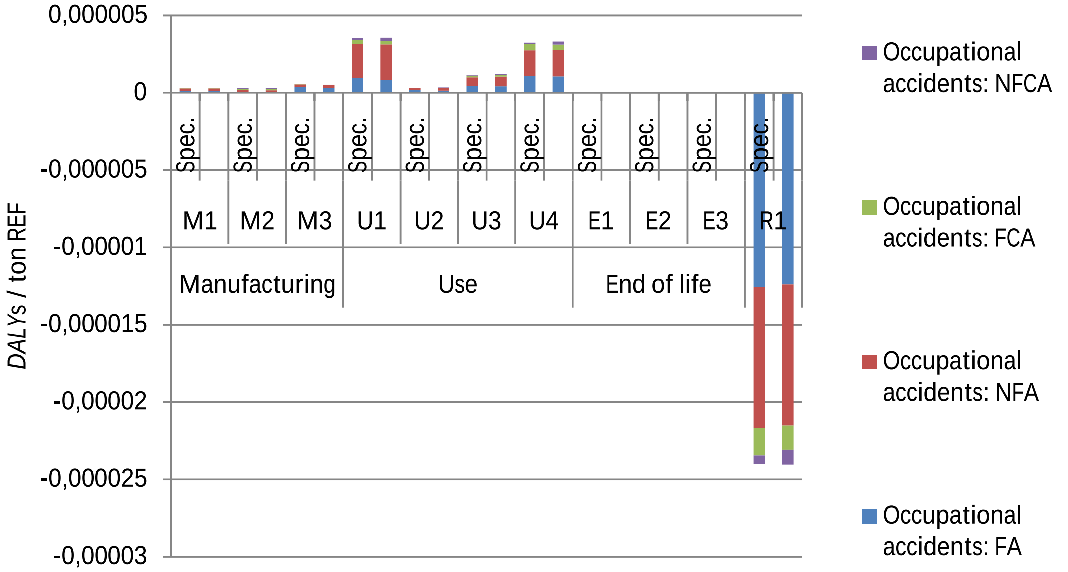

Figure 6.11. *Comparison of scenario A's LCIA results calculated using industry and area specific (indicated by "spec." in the figure), and average characterization factors*

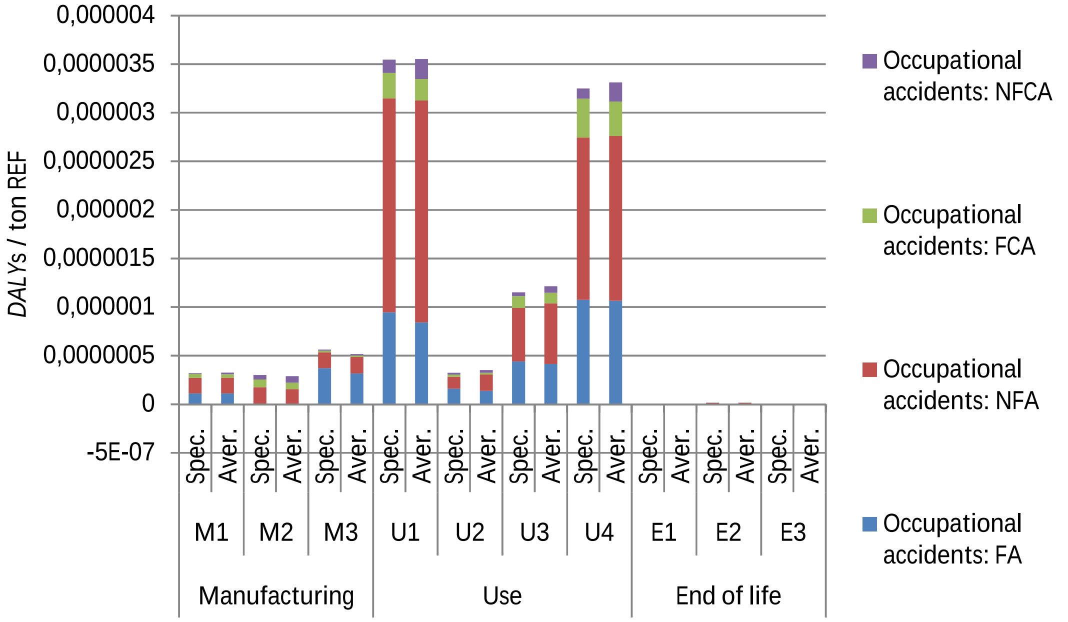

Figure 6.12. *Comparison of scenario B's LCIA results calculated using industry and area specific (indicated by "spec." in the figure), and average (indicated by "aver." In the figure) characterization factors*

Judging by the results of the comparison, the use of average characterization factors does not affect the overall results significantly. When breaking the results down, the use of average characterization factors does however seem to cause notable deviation in the results. The impacts caused by non-fatal commuting accidents are increased in both scenarios by almost 100%. The impacts caused by fatal commuting accidents on the other hand are decreased by up to 23%. For occupational accidents the deviations are smaller considering the overall results, but for individual processes the deviations can still reach up to 20% increase and up to 30% decrease in the end-point impacts.

The deviations caused by using average characterization factors can be expected to be even greater if more detailed data than what is used for this study is available. If however less detailed data is used, the deviations can be expected to be less significant as more processes are inventoried based on average data to begin with.

The question of whether or not to use industry and area specific characterization factors is therefore related to the data quality requirements of the study: in case detailed inventory data is intended to be collected, there is no point in using average characterization factors that lose some of the details. On the other hand, if the study is intended to create a quick overview of the system, average characterization factors should do the trick. In both cases it is still recommended to use separate characterization factors for commuting accidents, as their impacts are notably overestimated when using average characterization factors.

6.8 Possibility of using the results for improved safety

The basic procedure for improving occupational safety should be based on primarily preventing the element of danger from occurring. If not possible, it should be removed or replaced with a less dangerous element. Finally, if the element of danger cannot be removed or replaced either, the risk should be reduced by technical solutions. (Riikonen et al. 2003)

In order to be able to take the first steps in improving occupational safety, the elements of danger have to be identified first. LCA has on numerous occasions been proposed to be used for identifying the elements of danger on system level. The identified elements can then be studied in greater detail using different risk assessment tools. Such combined use of risk assessment (later on referred to as RA) tools and LCA can result in notable cost savings as the resources can be better focused on the most significant parts of the system. (e.g. Flemström et al. 2004; Tolle et a. 2001; Owens 1997)

The case study results show that it is possible to identify the most dangerous processes using LCA as a tool for assessing occupational safety. The level at which these processes are identified is rather high making it that there is only limited support for identifying the elements of danger posed by an individual process. Instead, LCA seems to be better suited for identifying them at a system level. On the other hand, this is partially a result of studying a very large system. Pettersen and Hertwich (2008) for example successfully applied a similar method to a smaller system indicating that the proposed method can be used also for more detailed identification of potential elements of danger. This of course means that the studied system has to be smaller than in the case study.

The proposed method also makes it possible to identify processes that may at first glance seem insignificant, but with closer inspection prove to be major contributors to the occupational health impacts. For instance in the studied case the mining and production of hard coal that is needed to produce cement for the stabilization of ashes is among the greatest individual sources of occupational health impacts. This suggests that the occupational health impacts associated with the disposal of ashes could be reduced by developing alternative solutions for the treatment of ashes. The identification of such intermediate impacts is extremely difficult using traditional risk assessment tools.

After identifying the potentially most dangerous elements they should be either prevented from occurring, or if not possible, removed or replaced with a less dangerous element. Preventing the element of danger from occurring or removing it can however result in shifting the dangers from one process to another. RA only poorly supports the identification of trade-offs between different systems or processes due to its limited scope (Linkov & Seager 2011). Using LCA to identify the connections between processes can therefore help minimize the risk of shifting the burden from one process to another and thus making it that the overall safety is not improved (e.g. Flemström et al. 2004; Tolle et al. 2001; Owens 1997). In this case for example reducing the particle size of REF could reduce the risks of failures in fuel handling system of the power plant and therefore lead to a reduced risk of disturbances in the system. This then again could help reduce the risks at the power plant, but could also lead to increased potential for accidents during the production of REF.

A further aspect in identifying possible trade-offs is that the combination of LCA and occupational safety can ensure that no trade-offs occur between environmental impacts and occupational safety. Numerous examples of such situations have been identified in the case study, as discussed in chapter 6.4. Again the focus of the case study was at a very high level and the results are therefore suitable only for identifying trade-offs at system level. Trade-offs can probably be identified also at process level if the system is limited to cover fewer processes at a more detailed level.

When removing or replacing elements of danger, one has to know the dangers of the new element in order to make sure that it is actually improving the situation. LCA is commonly used for numerous kinds of comparisons, and there is no reason why it couldn't be use to compare also the occupational safety issues of different systems, processes or products. Again a very high level example of this is presented by the comparison of two different energy production methods[20]. Bringing this down to process level is also possible as demonstrated by Pettersen and Hertwich (2008). Such comparison could also be useful

[20] The kind of comparison has not been presented here as such, but the outcomes represent basically a comparison against hard coal based energy generation put in a slightly different context.

for the studied case: the comparison of different technologies could be carried out to determine if the occupational health impacts could be reduced by replacing the cement used for the stabilization of ashes with another material or by using altogether different treatment method (e.g. thermal treatment of ashes).

Such comparisons however have to be subject to extreme caution. In the studied case it might seem beneficial to reduce transportation distances, as the transportations have a notable impact on occupational and foremost bystanders' health. At first glance reduced transportation distances might seem to result in reduced impacts on human health, but this can in fact be a false conclusion. As discussed in chapter 2.5.3, LCA studies often suffer from a loss of spatial information and are therefore not suited to support decision making regarding optimal locations of facilities. Also the non-linear relationships discussed in chapter 2.5.4 making it difficult to support such decision making given that the non-linear relationships on background processes are difficult to model without making the system increasingly complex. All in all, the proposed method supports conceptual modeling only poorly. Conceptual modeling would be required for determining the best way of avoiding trade-offs and for studying the impacts of improvements. The method should not therefore be used as a standalone tool, but rather to support other more sophisticated tools such as RA.

Improving the occupational safety requires also cooperation between different actors. In modern world the companies are not only responsible for their own backyard, but also for the backyards of their suppliers and in some cases even customers. As argued by Hendrickson and colleagues (2006), although numerous companies are paying attention for the safety of their own operations, they are not paying enough attention to the safety of their supply chains. In Metso these things are already being paid attention to, as the company has for example published a set of sustainability criteria for suppliers. These criteria include for example demands on work safety. The proposed method can however provide additional support by illustrating how big of an impact can actually be caused by the supply chains, and what parts of the supply chain are relatively speaking the most dangerous ones. Illustrating the impacts of supply chains can then work as a strong motivator both internally and externally. Identifying the relatively speaking most dangerous parts of supply chain can on the other hand help focus the resources on monitoring primarily these parts.

A part of good corporate citizenships is to also provide customers with information to help them improve their operations and monitor their supply chains. As the focus of LCA is most commonly on products, it is obvious that it can be used to provide customers with information. The case study for example demonstrated that the biggest impacts caused by occupational accidents are not directly linked to the product or its manufacturing, but the supply chains of the customer operating the product. Identifying these and communicating them to customers can help them in bringing occupational safety issues down to their supply chains.

6.9 Results relative to literature

According to Hofstetter and Norris (2003) the human health impacts caused by occupational accidents are in most cases about ten times smaller than the environmental health impacts and relatively speaking important only for sectors with low environmental impacts but hazardous working conditions. The findings of this study are for most parts in line with the findings of Hofstetter and Norris (2003): the majority of human health impacts are not caused by occupational accidents, but by the release of emissions. Also the statement that occupational accidents are relatively speaking important only for selected sectors is confirmed by the findings of this study.

Hofstetter and Norris (2003) also conclude that the majority of human health impacts resulting from occupational accidents are the result of fatal accidents. This is in line with the findings of Pettersen and Hertwich (2008), according to whom some 70% of the human health impacts are caused by fatal accidents. The results of the case study on the other hand indicate that product systems non-fatal accidents have a greater contribution to the human health impacts than the fatal accidents. In scenario B for example, non-fatal accidents account for over 60% of the health impacts caused by occupational accidents. The difference between the shares of fatal and non-fatal accidents in the case study and literature is not overwhelming, but still notable. On the other hand, Hofstetter and Norris (2003) estimated that the number of non-fatal accidents was probably underestimated in their study. The actual share of fatal accidents may therefore be smaller than they initially reported, which supports the outcomes of this study.

The results of this study also indicate that the commuting accidents can have a notable impact on the human health impacts caused by accidents. This is again in line with earlier findings, according to which the exclusion of commuting accidents can result in notable underestimation of human health impacts (Concha-Barrientos et al. 2005).

All in all, the results of this study are for most parts supported by those of earlier studies. There are some small differences in the results, but they can easily be the result of studying different geographical areas. Also the uncertainty of inventory data can be a contributor to the observed differences. On the other hand, uncertainty is not a unique characteristic of this study, but rather something that is reported to be associated with other similar studies as well.

7 Conclusions and recommendations

7.1 Possibility and feasibility of studying occupational safety in LCA

The first part of this study demonstrated that there is a clear desire for improving the LCA framework so that it covers not only environmental aspects, but also occupational safety. At the moment this is far from being standard practice, but it has still gained increasing attention. Also methods for doing this have been presented, many of which share the same elements. All in all, these things make it that it is technically possible to study occupational safety as a part of LCA.

The bigger question is whether or not it is practically possible. The outcomes of the case study are that including occupational safety in LCA is for some parts a rather laborious task. The data is for most parts available, but unlike data regarding environmental issues, it has not been complied in easy to use databases. Instead, the data has to be collected from various different sources. This is also indicated by the length of the reference list at the end of this thesis.

The use of data from numerous different sources is bound to increase the risk of inconsistency. This along with the unavoidable uncertainty is making the results less accurate and harder to interpret. The uncertainty is not a unique characteristic of this method or this study: in the end accidents usually result from numerous small mistakes, neglecting of safe working procedures and even unexpected behavior of people and machinery. There is always some degree of uncertainty involved when dealing with human behavior making it that studies such as this one are always exposed to it.

The study of occupational safety as a part of LCA cannot provide one with absolute values regarding the occurrence of occupational or commuting accidents. It also does not provide information on the risks associated with the product. These are inbuilt characteristics of the tool that have not been overcome as a part of this study. But LCA is still not useless even considering occupational safety issues. The results of the case study indicate that there is a severe risk of shifting the burden from environmental health impacts to occupational safety issues in case environmental life cycle assessment is the sole decision making criteria. Even more importantly, the case study demonstrates that excluding occupational safety issues from LCA can lead to opposite results than what would be obtained when also occupational health impacts were considered.

The limitation of the method is that it can only poorly be used for estimating the impacts of changing some parts of the process. In case these changes result in significant changes in the background system, the proposed method should not be used at all or at least a lot more detailed data is needed. This method also does not guide one in decreasing the potential for occupational accidents. This requires a lot more detailed data regarding the system and all its parts.

However, the method can help in identifying the potentially most dangerous parts of the system. It can also be used to ensure that product designers are aware of the possible outcomes of changing the system and that they resort to more detailed assessments in case their decisions can have an impact on occupational safety. This method can also be used in supporting decision making so that occupational safety issues are considered a decision making criteria. In the studied case the owner of the power plant for example cannot significantly decrease the impacts of occupational accidents associated with the use of the power plant. But by identifying which processes contribute to the impacts on human health, the owner can ensure that the companies taking care of these processes are selected based on their performance and commitment, and that they are audited and any omissions of occupational safety are interfered with.

The method can also be useful for identifying intermediate processes with high occupational safety risks that could easily escape the scope of traditional risk assessments. In some cases these processes can have notable impacts on the overall impacts of the product system. They can in some cases be also easily replaced by less harmful processes given that they are first identified. One of the benefits of using LCA for the study of occupational safety is that such intermediate processes can be identified with a lot less effort than would be needed if each process had to be studied separately using risk assessments.

If the concept of occupational safety is expanded to cover also other safety issues related to for example road traffic, the picture comes increasingly complex. The results of this study indicate that damages to bystanders can be even greater cause of impacts on human health than occupational accidents themselves. There is again also a risk shifting the burden from environmental health impacts or even occupational safety issues to damages on bystanders' health.

Given all these aspects of the issue, **it is essential that occupational safety is taken into account also from LCA perspective**. The quantitative method used in this study however requires a lot of work and is still of limited use. Therefore the further study of other applicable methods, including also qualitative ones, should be carried out to determine if a more effective method exists or could be developed.

7.2 Recommendations for future use of the method

The proposed method for studying occupational safety is an efficient tool in identifying potential trade-offs and elements of danger. The proposed method is indeed best used for identifying processes that pose notable relative risk of occupational accidents. These processes should then be studied using risk assessments and other more sophisticated tools. The main focus should not be on minimizing the working time associated with the product system as it basically transfers to higher employment and therefore is a positive impact on human wellbeing. Instead, the focus should be on determining methods for decreasing the accident frequency or replacing dangerous processes with less dangerous ones. The proposed method is not suited for identifying ways to reduce the accident frequency as it is its inbuilt function that the accident frequency is needed as an input to the system. It can however be used to compare different processes and systems to determine the least dangerous.

As the method is proven to be rather laborious, it is recommended that extensive quantitative assessments such as the case study are not used as the primary way of identifying the risks of trade-offs. Instead, it is recommended to use the method for a group of similar products to identify the processes that are most likely to cause notable impacts on human health. This will also help highlight the interactions between different processes. The most significant processes and interactions should then be studied using risk assessments to determine what are the key factors causing occupational accidents and what are therefore the properties of a specific product system that should be improved. The outcomes of the process should not be used only internally, but also externally to support the improvement of Metso Power’s customers’ and their suppliers’ occupational safety.

The external use of the method should not be limited to the communication of the results. As the outcomes of this study show, the background systems may have notable impact on the occupational health impacts of the studied system. The assessments should therefore be carried out in collaboration with all interested parties to ensure access to accurate case specific data. In case this cannot be done, the system boundaries should perhaps be more limited.

All in all, **the proposed method is limited for a number of reasons, but can and should still be used to support decision making or at least identify the deficiencies in existing methods used to support decision making**. The method should be further developed, and some ideas for this development are given in the following chapter.

7.3 Recommendations for future studies

Some questions are left unanswered and numerous new questions have emerged as a result of this thesis. For one, the role of other than workers has been very little studied considering occupational and other accidents. The results of this study indicate that it deserves much more attention in the future. A simplified method for involving bystanders into the framework was presented here, but it needs further development and better inventory data. The latter is lacking in many places indicating that there is also room for improvement regarding occupational safety statistics.

The second question that should be studied in the future is the possibility of using risk based LCA tools for studying occupational safety. Risk based tools have been presented for environmental impacts, and they could add some value for the study of occupational safety as well. Unfortunately, the risk based tools are not yet standard practice and therefore need further development. Also, no risk based tool was found that would support the study of occupational safety, and it is therefore worth investigating if such tool could be developed.

The risk based tools should support bottom up approach to inventory, meaning that the inventory data would not consist of static accident frequency. This would better support conceptual modeling and increase the usability of LCA when it comes to occupational safety. In this study a top down approach was used, which meant that accident frequency was needed as an input. Therefore no impacts on accident frequency could be studied here. Theoretically accident frequency could be treated as a variable, but the existing software does not support this.

Occupational accidents are just one aspect of occupational safety and wellbeing. The other aspects, for example occupational diseases, should be included as well. Such inclusions have been proposed in literature, but their applicability has not been studied here. However, using statistical data to assess occupational health would result in severe delay as many of the health problems are developed over many years time. A bottom up approach could therefore be better suited also for the other aspects of occupational safety.

Finally, in all cases databases are needed to support the inventory analysis and thus make it possible to use the methods on wider scale. The data provided as a part of this thesis provides one with a good starting point for inventory analysis, but is limited to the processes studied here and the method applied in this study. Therefore, the databases should be developed parallel to the inventory methods.

References

Accident Investigation Board. 2007. Turvallisuusselvitys tasoristeysonnettomuuksista (Safety study on level crossing accidents) [electronic report]. Helsinki, Tutkintaselostus S 1/2005 R. 223 p. [accessed on 23.8.2012]. Available at: http://www.turvallisuustutkinta.fi/Satellite?blobtable=MungoBlobs&blobcol=urldata&SSURIapptype=BlobServer&SSURIcontainer=Default&SSURIsession=false&blobkey=id&blobheadervalue1=inline;%20filename=hx3veaad8.pdf&SSURIsscontext=Satellite%20Server&blobwhere=1330439894211&blobheadername1=Content-Disposition&ssbinary=true&blobheader=application/pdf

Ajanko S., Moilanen A., Juvonen J. 2005. Jätteiden syntypaikkalajittelujärjestelmän ja käsittelytekniikan vaikutus kierrätyspolttoaineen laatuun [electronic report]. Espoo, VTT Tiedotteita 2317. 33 p. + appendices 21 p. [accessed on 23.8.2012]. Available at: http://www.vtt.fi/inf/pdf/tiedotteet/2005/T2317.pdf

Ancona C., Badaloni C., de Hoogh K., Krayer von Kraus M., Martuzzi M., Mataloni F., Mitis F., Palkovicova L., Porta D., Ranzi A., Forastiere F. 2010. Integrated Environmental and Health Impact Assessment of Waste Management in Lazio (Italy) [electronic report]. WP3.6 Waste, 2nd Pass Assessment Report. 36 p. + appendices 27 p. [accessed on 23.8.2012]. Available at: http://www.integrated-assessment.eu/content/integrated_environmental_and_health_impact_assessment_waste_management_lazio_italy

Antikainen 2010. Elinkaarimetodiikkojen nykytila, hyvät käytännöt ja kehitystarpeet (Life cycle methods: current use, best practices and development needs) [electronic report]. Helsinki, Suomen ympäristökeskuksen raportteja 7/2010. 83 p. [accessed on 23.8.2012]. Available at: http://www.ymparisto.fi/default.asp?contentid=356886&lan=fi

Antikainen R., Seppälä J., Grönroos J., Korhonen M.-R., Koskela S., Manninen K., Mattila T., Schultz E., Tuominen M., Gustafsson M., Baumgartner R., Korhonen J., Tsvetkova A., Helin T., Häkkinen T., Ovaskainen M., Pingoud K., Soimakallio S., Sokka L., Tonteri H., Vares S., Wessman H., Angerman M., Heino J., Suopajärvi H., Dahl O., Husgafvel R. 2012. Elinkaarimenetelmät yrityksen päätöksenteon tukena – FINLCA-hankkeen loppuraportti [electronic report]. Helsinki, The Finnish Environment 10/2012. 90 p.

[accessed on 23.8.2012]. Available at: http://www.ymparisto.fi/default.asp?contentid=407198&lan=fi

Baer J. Hofstetter P., Pennington D., Udo de haes H. 2000. Life Cycle Impact Assessment Workshop Summary: Midpoints versus Endpoints: The Sacrifices and Benefits. The International Hournal of Life Cycle Assessment, 5, 6, pp. 319-326.

Bauer C. 2008. Life Cycle Assessment of Fossil and Biomass Power Generation Chains, an analysis carried out for ALSTOM Power Services [electronic report]. Villingen, PSI Bericht Nr. 08-05. 68 p. [accessed on 23.8.2012]. Available at: http://gabe.web.psi.ch/pdfs/PSI_Report/PSI-Bericht%2008-05.pdf

Bauer C., Heck T., Dones R., Mayer-Spohn O., Blesl L. 2008. Final report on technical data, costs, and life cycle inventories of advanced fossil power generation systems [electronic report]. Stuttgart, NEEDS – New Energy Externalities Developments for Sustainability, Deliverable n° 7.2 - RS 1a. 166 p. + appendices 99 p. [accessed on 23.8.2012]. Available at: http://www.needs-project.org/docs/RS1a%20D7.2%20Final%20report%20on%20advanced%20fossil%20power%20plants.pdf

Begg S., Tomijima N. 2000. Global burden of injury in the year 2000: an overview of methods [electronic report]. Geneva, Global Burden of Disease 2000, Draft 15-08-06. 22 p. [accessed on 23.8.2012]. Available at: http://www.who.int/healthinfo/statistics/bod_injuries.pdf

Benoît C., Norris G., Valdivia S., Ciroth A., Moberg A., Bos U., Prakash S., Ugaya C., Beck T. 2010. The guidelines for social life cycle assessment of products: just in time! International Journal of Life Cycle Assessment, 15, 2, pp. 156-163

Berry J., Holland M., Lee D., McConville A., Watkiss P., Friedrich R., Krewitt W., Mayerhofer P., Staiger B., Truckenmüller A., Eyre N., Hurley F., MacLaren W., Tran L., Waclawski E., Hornung M., Howard P., Howard D., Westrich B., Wuest W., Markandya A., Rhodes B., Gressman A., Weltshev M., Kölling M. 1995. Coal & Lignite [electronic report]. Luxembourg, ExternE studies Vol. 3. 571 p. [accessed on 23.8.2012]. Available at: http://www.externe.info/externe_d7/?q=node/38

Bras-Klapwijk R. 1998. Are Life Cycle Assessments a Threat to Sound Public Policy Making? International Journal of Life Cycle Assessment, 3, 6, pp. 333-342.

Cabrita J., Ortigão M. 2011. Working time developments – 2010. [WWW]. [accessed on 23.8.2012]. Available at: http://www.eurofound.europa.eu/eiro/studies/tn1106010s/tn1106010s.htm

Ciroth A., Franze J. 2011. LCA of an Ecolabeled Notebook – Consideration of Social and Environmental Impacts Along the Entire Life Cycle [electronic report]. Berlin, GreenDeltaTC GmbH. 169 p. + appendices 238 p. [accessed on 02.10.2012]. Available at: http://www.greendeltatc.com/uploads/media/LCA_laptop_final.pdf

Classen M., Althaus H.-J., Blaser S., Scharnhorst W., Tuchsmid M., Jungbluth N., Faist Emmenegger M. 2009. Life Cycle Inventories of Metals. Dübendorf, ecoinvent report No. 10. 920 p.

Clift R., Doig A., Finnveden G. 2000. The Application of Life Cycle Assessment to Integrated Solid Waste Management: Part 1 – Methodology. Process Safety and Environmental Protection, 78, 4, pp. 279-287.

Concha-Barrientos M., Imel Nelson D., Fingerhut M., Driscoll T., Leigh J. 2005. The Global Burden Due to Occupational Injury. American Journal of Industrial Medicine, 48, 6, pp. 470-481.

Cooper J., Fava J. 2006. Life-Cycle Assessment – Practitioner Survey. Journal of Industrial Ecology, 15, 6, pp. 817-820.

Cowell S., Fairman R., Lofstedt R. 2002. Use of Risk Assessment and Life Cycle Assessment in Decision Making: A Common Policy Research Agenda. Risk Analysis, 22, 5, pp. 879-894.

Curran M. 2006. Life Cycle Assessment: Principles and Practice [electronic report]. Reston, EPA/600/R-06/060. 62 p. + appendices 18 p. [accessed on 23.8.2012]. Available at: http://www.epa.gov/nrmrl/std/lca/lca.html

Dalhammar C. 2007. An Emerging Product Approach in Environmental Law: Incorporating the life cycle perspective. Doctoral dissertation. Lund. Lund University, The International Institute for Industrial Environmental Economics (IIIEE). 460 p.

Danish Maritime Authority. 2009. Marine Accidents 2009 [electronic report]. Copenhagen. 51 p. + appendices 6 p. [accessed on 23.8.2012]. Available at: http://www.dma.dk/SiteCollectionDocuments/Publikationer/Maritime-accidents/Accidents%20at%20Sea%202009.pdf

De Benedetto L., Klemeš J. 2009. The Environmental Performance Strategy Map: an integrated LCA approach to support the strategic decision-making process. Journal of Cleaner Production, 17, 10, pp. 900-906.

Del Borghi A., Gallo M., Del Borghi M. 2009. A survey of life cycle approaches in waste management. The International Journal of Life Cycle Assessment, 14, 7, pp. 597-610.

Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste

Doka G. 2003. Life Cycle Inventories of Waste Treatment Service, Part II: Waste Incineration. St Galen, ecoinvent report No. 13. 91 p.

Doka G. 2009a. Life Cycle Inventories of Waste Treatment Service, Part III: Landfills – Underground deposits - Landfarming. Dübendorf, ecoinvent report No. 13. 133 p.

Doka G. 2009b. Life Cycle Inventories of Waste Treatment Service, Part V: Building Material Disposal. Dübendorf, ecoinvent report No. 13.53 p.

Dones R., Bauer C., Röder A. 2007. Kohle. In: Dones R., Bauer C., Bolliger R., Burger B., Faist Emmenegger M., Frischknecht R., Heck T., Jungbluth N., Röder A., Tuchschmid A. Sachbilanzen von Energiesystemen: Grundlagen für den Ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Dübendorf, ecoinvent report No. 6. 334 p.

Dupré D. 2001. Statistics in Focus: Accidents at work in the EU 1998-1999 [electronic report]. Statistics in Focus, Theme 3, 16/2001. 7 p. [accessed on 23.8.2012]. Available at: http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-NK-01-016/EN/KS-NK-01-016-EN.PDF

Ekholm E., Korkala R., Nummela E. 2005. REF -laitosten tarve- ja toimivuusselvitys [electronic report]. 67 p. + appendices 4 p. [accessed on 23.8.2012]. Available at: http://www.jly.fi/REF-laitosselvitys_loppuraportti.pdf

Ekvall T., Assefa G., Björklund A., Eriksson O., Finnveden G. 2007. What life-cycle assessment does and does not do in assessments of waste management. Waste management, 27, 8, pp. 989–996

Ekvall T., Finnveden G. 2000. The Application of Life Cycle Assessment to Integrated Solid Waste Management – Part 2: Perspectives on Energy and Material Recovery from Paper. Process Safety and Environmental Protection, 78, 4, pp. 288-294.

Etelä-Karjalan Jätehuolto Oy. 2011. Tiedote ekovoimalaitoshankkeesta. [PDF]. [accessed on 23.8.2012]. Available at: http://www.ekjh.fi/Dokumentit/TIEDOTE_EKOVOIMA.pdf

Eurogip. 2009a. Statistical review of occupational injuries: Austria, 2008 data [electronic report]. Paris, Ref. Eurogip-46/E. 18 p. [accessed on 23.8.2012]. Available at: http://www.eurogip.fr/en/docs/Eurogip_Point_stat_Au08_46EN.pdf

Eurogip. 2009b. Statistical review of occupational injuries: Spain, 2007 data [electronic report]. Paris, Ref. Eurogip-36/E. 23 p. [accessed on 23.8.2012]. Available at: http://www.eurogip.fr/en/docs/Eurogip_Point_stat_Es07_36EN.pdf

Eurogip. 2010a. Statistical review of occupational injuries: Belgium, 2008 data [electronic report]. Paris, Ref. Eurogip-56/E. 25 p. [accessed on 23.8.2012]. Available at: http://www.eurogip.fr/en/docs/Eurogip_Point_stat_Bel08_56EN.pdf

Eurogip. 2010b. Statistical review of occupational injuries: Italy, 2008 data [electronic report]. Paris, Ref. Eurogip-50/E. 18 p. [accessed on 23.8.2012]. Available at: http://www.eurogip.fr/en/docs/Eurogip_Point_stat_It08_50EN.pdf

Eurogip. 2010c. Statistical review of occupational injuries: France, 2009 data [electronic report]. Paris, Ref. Eurogip-60/E. 18 p. [accessed on 23.8.2012]. Available at: http://www.eurogip.fr/en/docs/Eurogip_Point_stat_Fr09_60EN.pdf

Eurogip. 2010d. Statistical review of occupational injuries: Spain, 2009 data [electronic report]. Paris, Ref. Eurogip-58/E. 32 p. [accessed on 23.8.2012]. Available at: http://www.eurogip.fr/en/docs/Eurogip_Point_stat_Es09_58E.pdf

Eurogip. 2011. Statistical review of occupational injuries: Sweden, 2008-2009 data [electronic report]. Paris, Ref. Eurogip-65/E. 19 p. [accessed on 23.8.2012]. Available at: http://www.eurogip.fr/en/docs/Eurogip_Point_stat_Sweden_08_09EN.pdf

Eurogip. 2012. Statistical review of occupational injuries: Germany, 2009-2010 data [electronic report]. Paris, Ref. Eurogip-71/E. 27 p. [accessed on 23.8.2012]. Available at: http://www.eurogip.fr/en/docs/Eurogip_Point_stat_GER0910_71EN.pdf

European Commission. 2006. Integrated Pollution Prevention and Control: Reference Document on the Best Available Techniques for Waste Incineration [electronic report]. 488 p. + appendices 114 p. [accessed on 23.8.2012]. Available at: http://eippcb.jrc.es/reference/wi.html

European Commission. 2007. Recommendations for life cycle based Indicators for Sustainable Consumption and Production in the European Union. Outcomes of the 3rd International Life Cycle Thinking Workshop on “Sustainability and Decoupling Indicators: Life cycle based approaches”, Cyprus, January 22-23, 2007. 30 p. [accessed on 23.8.2012]. Available at: http://lct.jrc.ec.europa.eu/pdf-directory/Recommendations%20for%20life%20cycle%20based%20Indicators.pdf

European Commission. 2010a. International Reference Life Cycle Data System (ILCD) Handbook: General guide for Life Cycle Assessment - Detailed guidance [electronic report]. Luxembourg, EUR 24708 EN. 322 p. + appendices 72 p. [accessed on 23.8.2012]. Available at: http://lct.jrc.ec.europa.eu/pdf-directory/ILCD-Handbook-General-guide-for-LCA-DETAIL-online-12March2010.pdf

European Commission. 2010b. International Reference Life Cycle Data System (ILCD) Handbook: Framework and requirements for LCIA models and indicators [electronic report]. Luxembourg, EUR 24586 EN. 95 p. + appendices 18 p. [accessed on 23.8.2012]. Available at: http://lct.jrc.ec.europa.eu/pdf-directory/ILCD-Handbook-LCIA-Framework-requirements-online-12March2010.pdf

European Commission. 2010c. International Reference Life Cycle Data System (ILCD) Handbook: Analysing of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment [electronic report]. 72 p. + appendices 33 p. [accessed on 23.8.2012]. Available at: http://lct.jrc.ec.europa.eu/pdf-directory/ILCD-Handbook-LCIA-Background-analysis-online-12March2010.pdf

European Commission. 2010d. International Reference Life Cycle Data System (ILCD) Handbook: Specific guide for Life Cycle Inventory (LCI) data sets [electronic report]. Luxembourg, EUR 24709 EN. 105 p. + appendices 24 p. [accessed on 23.8.2012]. Available at: http://lct.jrc.ec.europa.eu/pdf-directory/ILCD-Handbook-Specific-guide-for-LCI-online-12March2010.pdf

European Commission. 2010e. Report from the commission to the council and the European parliament on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling [electronic report]. Brussels, COM(2010)11 final. 10 p. + appendices 9 p. [accessed on 23.8.2012]. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52010DC0011:EN:NOT

European Commission. 2010f. Commission Staff Working Document: Impact Assessment Accompanying document to the Proposal for a Council Regulation on State aid to facilitate the closure of uncompetitive coal mines [electronic report]. Brussels, SEC(2010) 850. 63 p.

[accessed on 23.8.2012]. Available at: http://ec.europa.eu/governance/impact/commission_guidelines/docs/sec_2010_850_ia_state_aid_coal_en.pdf

European Commission. 2010g. Our Thinking – Life Cycle Thinking. [WWW]. [accessed on 23.8.2012]. Available at: http://lct.jrc.ec.europa.eu/index_jrc

European Commission. 2011a. Impact Assessment Accompanying the Document Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions: Energy Roadmap 2050, part 1/2 [electronic report]. Brussels. SEC(2011) 1565/2. [accessed on 27.8.2012]. Available at: http://ec.europa.eu/energy/energy2020/roadmap/doc/sec_2011_1565_part1.pdf

European Commission. 2011b. Impact Assessment Accompanying the Document Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions: Energy Roadmap 2050, part 2/2 [electronic report]. Brussels. SEC(2011) 1565. [accessed on 27.8.2012]. Available at: http://ec.europa.eu/energy/energy2020/roadmap/doc/sec_2011_1565_part2.pdf

European Commission. 2012. European Platform on Life Cycle Assessment (LCA). [WWW]. [accessed on 23.8.2012]. Available at: http://ec.europa.eu/environment/ipp/lca.htm

Eurostat. 2009. Causes and circumstances of accidents at work in the EU [electronic report]. Luxembourg, KE-78-09-668-EN-C. 231 p. [accessed on 23.8.2012]. Available at: http://epp.eurostat.ec.europa.eu/portal/page/portal/health/documents/phase_3_causes_circumstances.pdf

Eurostat. 2011. Eurostat metadata: Accidents at work (ESAW) - until 2007. [WWW]. [accessed on 23.8.2012]. Available at: http://epp.eurostat.ec.europa.eu/cache/ITY_SDDS/EN/hsw_acc7_work_esms.htm

Eurostat. 2012a. Accidents at work by type of injury and severity (NACE Rev. 2: A_C-N) (hsw_mi07) [database]. Luxembourg, Health and safety at work: Accidents at work (ESAW) – 2008 onwards. [accessed on 23.8.2012]. Available at: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=hsw_mi07&lang=en

Eurostat. 2012b. Number of accidents at work by type of injury and severity (hsw_aw_ninsv) [database]. Luxembourg, Health and safety at work: Accidents at work

(ESAW) – until 2007. [accessed on 23.8.2012]. Available at: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=hsw_aw_ninsv&lang=en

Eurostat. 2012c. Accidents at work by economic activity and type of injury (hsw_n2_07) [database]. Luxembourg, Health and safety at work: Accidents at work (ESAW) – 2008 onwards. [accessed on 23.8.2012]. Available at: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=hsw_n2_07&lang=en

Eurostat. 2012d. Life expectancy by age and sex (demo_mlexpec) [database]. Luxembourg, Population: mortality. [accessed on 23.8.2012]. Available at: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=demo_mlexpec&lang=en

Eurostat. 2012e. Accidents at work by sex and age (NACE Rev. 2: A_C-N) (hsw_mi01) [database]. Luxembourg, Health and safety at work: Accidents at work (ESAW) – 2008 onwards. [accessed on 23.8.2012]. Available at: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=hsw_mi01&lang=en

Eurostat. 2012f. Standardised incidence rate of accidents at work by economic activity, severity and sex (hsw_aw_inasx) [database]. Luxembourg, Health and safety at work: Accidents at work (ESAW) – until 2007. [accessed on 23.8.2012]. Available at: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=hsw_aw_inasx&lang=en

Eurostat. 2012g. Non-fatal accidents at work by economic activity and sex (hsw_n2_01) [database]. Luxembourg, Health and safety at work: Accidents at work (ESAW) – 2008 onwards. [accessed on 23.8.2012]. Available at: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=hsw_n2_01&lang=en

Eurostat. 2012h. Fatal accidents at work by economic activity (hsw_n2_02) [database]. Luxembourg, Health and safety at work: Accidents at work (ESAW) – 2008 onwards. [accessed on 23.8.2012]. Available at: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=hsw_n2_02&lang=en

Eurostat. 2012i. Employees by sex, age and economic activity (from 2008, NACE rev.2) (lfsq_eegan2) [database]. Luxembourg, LFS series - Detailed quarterly survey results (from 1998). [accessed on 23.8.2012]. Available at: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=lfsq_eegan2&lang=en

Federation of Accident Insurance Institutions. 2011. Tilastojulkaisu 2011 [electronic report]. Helsinki, Työtapaturmat: Tilastovuodet 2001 – 2010. 23 p. + appendices 20 p. [accessed on 23.8.2012]. Available at: http://www.tvl.fi/www/page/tvl_www_8811

Finnish Environment Institute. 2001. Finnish Expert Report on Best Available Techniques in Large Combustion Plants [electronic report]. Helsinki, The Finnish Environment 458. 122 p. + appendices 21 p. [accessed on 23.8.2012]. Available at: http://www.ymparisto.fi/download.asp?contentid=10766

Finnish Transport Agency. 2011. The Finnish railway statistics 2011 [electronic report]. Helsinki, Liikenneviraston tilastoja 5/2011. 52 p. [accessed on 23.8.2012]. Available at: http://www2.liikennevirasto.fi/julkaisut/pdf3/lti_2011-05_suomen_rautatietilasto_web.pdf

Finnsementti. 2012a. Ympäristöraportti 2012 [electronic report]. 28 p. [accessed on 23.8.2012]. Available at: http://www.pinta.fi/asiakkaat/finnsementti/ymparistoraportti2012/

Finnsementti. 2012b. Avainlukuja vuonna 2011. [WWW]. [accessed on 23.8.2012]. Available at: http://www.finnsementti.fi/yritys/lukuja

Finnveden G. 1999. Methodological aspects of life cycle assessment of integrated solid waste management systems. Resources, Conservation and Recycling, 26, 3-4, pp. 173-187.

Finnveden G. 2000. On the Limitations of Life Cycle Assessment and Environmental Systems Analysis Tools in General. The International Journal of Life Cycle Assessment, 5, 4, pp. 229-238.

Finnveden G., Hauschild M., Ekvall T., Guinée J., Heijungs R., Hellweg S., Koehler A., Pennington D., Suh S. 2009. Recent Developments in Life Cycle Assessment. Journal of Environmental Management, 91, 1, pp. 1-21

Finnveden G., Johansson J., Lind P., Moberg Å. 2005. Life cycle assessment of energy from solid waste – part 1: general methodology and results. Journal of Cleaner Production, 13, 3, pp. 213-229.

Finnveden G., Lindfors L.-G. 1998. Data Quality of Life Cycle Inventory Data – Rules of Thumb. The International Journal of Life Cycle Assessment, 3, 2, pp. 65-66.

Flemström K., Carlson R., Erixon M. 2004. Relationships between Life Cycle Assessment and Risk Assessment – Potentials and Obstacles [electronic report]. Stockholm, The Swedish Environmental Protection Agency Report 5379. 80 p. [accessed on 23.8.2012]. Available at: http://www.naturvardsverket.se/Documents/publikationer/620-5379-5.pdf

Flyktman M. 2009. Turve Suomen kansantaloudessa. [PDF]. [accessed on 23.8.2012]. Available at:

http://www.turveteollisuusliitto.fi/user_files2/Turve%20Suomen%20kansantaloudessa%2021102009%20%284%29.pdf

Forbes M., Abelson P., Driscol T. 2006. Valuing the mortality and morbidity of work related injury and illness: a life-cycle costing of incidents reported in NSW in 2000-2001 [electronic report]. Sydney, Publications of NSW Injury Risk Management Research Centre, The University of New South Wales. 30 p. + appendices 97 p. [accessed on 23.8.2012]. Available at: http://www.irmrc.unsw.edu.au/documents/IRMRC%20Work%20Cover%20Report%20Sept06.pdf

Frankl P., Rubik F. 1999. Life-Cycle Assessment (LCA) in Business: An Overview on Drivers, Applications, Issues and Future Perspectives [electronic journal]. Global Nest: the International Journal, 1, 3, pp. 185-194. [accessed on 23.8.2012]. Available at: http://www.gnest.org/journal/Vol1_No3/Frankl.pdf

Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Heck T., Hellweg S., Hischier R., Nemecek T., Rebitzer G., Spielmann M., Wernet G. 2007. Overview and Methodology. Dübendorf, ecoinvent report No. 1. 68 p.

Gheewala S. 2009. LCA of waste management systems – research opportunities. The International Journal of Life Cycle Assessment, 14, 7, pp. 589-590.

Goedkoop M., Spriensma R. 2001. The Eco-indicator 99 – A damage oriented method for Life Cycle Impact Assessment, Methodology Report [electronic report]. Amersfoort, PRé Consultants nr. 1999/36A. 111 p. + appendices 21 p. [accessed on 23.8.2012]. Available at: http://www.pre-sustainability.com/download/misc/EI99_methodology_v3.pdf

Gómez D., Watterson J., Americano B., Ha C., Marland G., Matsika E., Nenge Namayanga L., Osman-Elasha B., Kalenga Saka J., Treanton K., Quadrelli R. 2006. Stationary Combustion [electronic report]. Hayama, 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 2, Energy. 47 p. [accessed on 23.8.2012]. Available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf

Guinée J., Gorée M., Heijungs R., Huppes G., Kleijn R., de Konig R., van Oers L., Wegener Sleeswijk A., Suh S., de Haes U., de Bruijn H., van Duin R., Huijbregts M., Lindeijer E., Roorda A., van der Ven B., Weidema B. 2001. Handbook on Life Cycle Assessment – Operational Guide to the ISO Standards. Dordrecht, Kluwer Academic Publishers. 692 p.

Hallikainen A., Rautala T., Karlström U., Kostamo P., Koivisto P., Pohjanvirta R., Hietaniemi V., Rajakangas L., Tuomaala V., Kankaanpää H., Verta M., Kostiainen E., Kurttio P., Turtiainen T., Kiviranta H., Komulainen H., Rantakokko P., Viluksela M., Niemi E., Nuotio K., Siivinen K. 2010. The chemical contaminants of foodstuffs and household water [electronic report]. Helsinki, Evira publications 15/2010. [accessed on 27.8.2012]. Available at: http://www.evira.fi/portal/fi/evira/julkaisut/?a=view&productId=198

Halonen P., Helynen S., Flyktman M., Kallio E., Kallio M., Paappanen T., Vesterinen P. 2003. Bioenergian tuotanto- ja käyttöketjut sekä niiden suorat työllisyysvaikutukset [electronic report]. Espoo, VTT tiedotteita 2219. [accessed on 23.8.2012]. Available at: http://www.vtt.fi/inf/pdf/tiedotteet/2003/T2219.pdf

Hämäläinen P., Takala J., Saarela K. L. 2006. Global estimates of occupational accidents. Safety Science, 44, 2, pp. 137–156.

Hämeen ympäristökeskus. 2005. Ympäristölupapäätös, Dnro HAM-2005-Y-169-111, Nro YLO/lup/167/05. [accessed on 23.8.2012]. Available at: http://www.ymparisto.fi/download.asp?contentid=43264&lan=fi

Hansen H., Nielsen D., Frydenberg M. 2002. Occupational accidents aboard merchant ships. Occupational & Environmental Medicine, 59, 2, pp. 85-91.

Heikkinen M., Hyvönen S., Juvonen J., Kiema M., Lohiniva E., Mäkinen T., Puurunen T., Ruokojärvi A., Torvinen S. 2002. KELPO-hanke: Kierrätyspolttoaineiden energiakäyttöselvitys Pohjois-Savossa – Yhteistarkastelu yhdyskuntalietteiden, hakkuutähteiden ja peltobiomassojen kanssa [electronic report]. KELPO-raportti 5.3.2002. 75 p. + appendices 23 p. [accessed on 23.8.2012]. Available at: http://gate.savonia-amk.fi/img/amk/sisalto/teknologia_ja_ymparisto/ymparistotekniikka/KELPO-loppuraportti.pdf

Hellweg S. 2000. Time- and Site-Dependent Life-Cycle Assessment of Thermal Waste Treatment Processes. Doctoral dissertation. Zurich, Swiss Federal Institute of Technology. 174 p.

Hellweg S., Demou E., Scheringer M., McKone T., Hungerbühler K. 2005. Confronting Workplace Exposure to Chemicals with LCA: Examples of Trichloroethylene and Perchloroethylene in Metal Degreasing and Dry Cleaning. Environmental Science & Technology, 39, 19, pp. 7741-7748

Hendrickson C., Lave L., Matthews H. 2006. Environmental Life Cycle Assessment of Goods and Services – An Input-Output Approach. Washington, resources for the Future. 259 p.

Hischier R., Weidema B., Althaus H.-J., Bauer C., Doka G., Dones R., Frischknecht R., Hellweg S., Humbert S., Jungbluth N., Köllner T., Loerincik Y., Margni M, Nemeck T. 2010. Implementation of Life Cycle Impact Assessment Methods. Dübendorf, ecoinvent report No. 3. 163 p.

Hofstetter P., Norris G. 2003. Why and how should we assess occupational health impacts in integrated product policy? Environmental science & technology, 37, 10, pp. 2025-2035

Honkapuro S., Jauhiainen N., Partanen J., Valkealahti S. 2009. Sähkön ja kaukolämmön rooli energiatehokkuudessa ja energian säästössä [electronic report]. Helsinki, Energiateollisuus Raportti 12.10.2009. 131 p. [accessed on 23.8.2012]. Available at: http://www.energia.fi/sites/default/files/sahko_ja_kaukolampo_energiatehokkuudessa_20091112_0.pdf

Honkasalo A. 2000. Occupational health and safety and environmental management systems. Environmental Science & Policy, 3, 1, pp. 39-45.

International Association of Oil & Gas Producers. 2010. Water transport accident statistics [electronic report]. London, Risk Assessment Data Directory Report No. 434 – 10. 16 p. [accessed on 23.8.2012]. Available at: http://www.ogp.org.uk/pubs/434-10.pdf

ISO 14040. 2006. Environmental management – Life cycle assessment – Principles and framework. 20 p.

ISO 14044. 2006. Environmental management – Life cycle assessment – Requirements and guidelines. 46 p.

ISO/TR 14062. 2002. Environmental management. Integrating environmental aspects into product design and development. 24 p.

Jensen A., Hoffman L., Møller B., Schmidt A., Christiansen K., Berendsen S., Elkington J., van Dijk F. 1997. Life Cycle Assessment (LCA) – A guide to approaches, experiences and information sources [electronic report]. Copenhagen, Environmental issue report No 6. 119 p. [accessed on 23.8.2012]. Available at: http://www.eea.europa.eu/publications/GH-07-97-595-EN-C

Johnke B. 1999. Emissions from Waste Incineration [electronic report]. Montreal, Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. 18 p. [accessed on 23.8.2012]. Available at: http://www.ipcc-nggip.iges.or.jp/public/gp/bgp/5_3_Waste_Incineration.pdf

Johnson E. 2008. Goodbye to carbon neutral: getting biomass footprints right. Environmental Impact Assessment Review, 29, 3, pp. 165-168.

Jolliet O., Müller-Wenk R., Bare J., Brent A., Goedkoops M., Heijungs R., Intsubo N., Peña C., Pennington D., Potting J., Rebitzer G., Stewart M., de Haes U., Weidema B. 2004. The LCIA Midpoint-damage Framework of the UNEP/SETAC Life Cycle Initiative. International Journal of Life Cycle Assessment, 9, 6, pp. 394-404

Jönsson, Å. 2000. Is it feasible to address indoor climate issues in LCA? Environmental Impact Assessment Review, 20, 2, pp. 241–259.

Jørgensen A., Hauschild M., Jørgensen M., Wangel A. 2009. Relevance and feasibility of social life cycle assessment from a company perspective. The International Journal of Life Cycle Assessment, 14, 3, pp. 204-214.

Jørgensen A., Le Bocq A., Nazarkina L., Hauschild M. 2008. Methodologies for Social Life Cycle Assessment. International Journal of Life Cycle Assessment, 13, 2, pp. 96-103.

Jungbluth N. 2007. Erdöl. In: Dones R., Bauer C., Bolliger R., Burger B., Faist Emmenegger M., Frischknecht R., Heck T., Jungbluth N., Röder A., Tuchschmid A. Sachbilanzen von Energiesystemen: Grundlagen für den Ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Dübendorf, ecoinvent report No. 6. 315 p.

Kaartinen T., Laine-Ylijoki J., Wahlström M. 2007. Jätteen termisen käsittelyn tuhkien ja kuonien käsittely- ja sijoitusmahdollisuudet [electronic report]. Espoo, VTT tiedotteita 2411. [accessed on 2.10.2012]. Available at: http://www.vtt.fi/inf/pdf/tiedotteet/2007/T2411.pdf

Kallio M., Lahtomäki R., Himanka T., Teeri T., Virta M., Järvinen A., Lyytikäinen M., Nuora M., Peltomäki K., Permi S., Järvinen J., Hedström I., peltonen L., Pasanen S., Talja R., Korvenoja A., Huuskonen A. 2011. Life Cycle Assessment – LT106. Unpublished report.

Kellenberger D., Althaus H.-J., Künniger T., Lehmann M., Jungbluth N., Thalmann P. 2007. Life Cycle Inventories of Building Products. Dübendorf, ecoinvent report No. 7. 899 p.

Kim I., Hur T. 2009. Integration of working environment into life cycle assessment framework. International Journal of Life Cycle Assessment, 14, 4, pp. 290-301.

Klöpffer W. 2008. Life Cycle Sustainability Assessment of Products (with Comments by Helias A. Udo de Haes, p. 95). International Journal of Life Cycle Assessment, 13, 5, pp. 89–95

Koisti O.-P. 2011. Käyttökohdeselvitys puun energiajakeiden käytöstä Kanta- ja Päijät-Hämeessä 2009 [electronic report]. In: Koisti O.-P., Rantala J., Laine A. 2011. Metsä- ja peltoenergiaselvitys 2011. Hämeen bioenergiahanke II. [accessed on 23.8.2012]. Available at: http://www.metsakeskus.fi/fi_FI/c/document_library/get_file?uuid=16a7e58b-3d3d-496e-9466-c393ac36bfd3&groupId=10156

Koneczny K., Pennington D. 2007. Environmental Assessment of Municipal Waste Management Scenarios: Part II – Detailed Life Cycle Assessments [electronic report]. Luxembourg, EUR 23021 EN/2. 176 p. + appendices 4 p. [accessed on 23.8.2012]. Available at: http://viso.jrc.ec.europa.eu/lca-waste-partII.pdf

Laanilan Voima Oy. 2009. Voimalaitoshanke: Ympäristövaikutusten arviointiselostus [electronic report]. Oulu, ENVI-501. 121 p. + appendices 17 p. [accessed on 23.8.2012]. Available at: http://www.ymparisto.fi/download.asp?contentid=110516&lan=fi

Lahti Energia. 2004. Jätepolttoaineen energiahyötykäyttöhankkeen YVA-ohjelma [electronic report]. 51 p. [accessed on 23.8.2012]. Available at: http://www.lahtienergia.fi/content/download/479/2509/file/YVA-ohjelma.pdf

Lahti Energia. 2005. Kierrätyspolttoaineen energiahyötykäyttöhanke: ympäristövaikutusten arviointiselostus [electronic report]. 55 p. [accessed on 23.8.2012]. Available at: http://www.eib.org/attachments/pipeline/20090604_eia1_fi.pdf

Leigh J., Markowitz S., Fahs M., Landrigan P. 2000. Cost of Occupational Injuries and Illnesses. [WWW]. [accessed on 23.8.2012]. Available at: http://www.pbs.org/wgbh/pages/frontline/shows/workplace/etc/cost.html

Lewandowska A., Wawrzynkiewicz Z., Noskowiak A., Foltynowicz Z. 2008. Adaptation of ecoinvent database to Polish conditions. The International Journal of Life Cycle Assessment, 13, 4, pp. 319-327.

Linkov I., Seager T.P. 2011. Coupling Multi-Criteria Decision Analysis, Life-Cycle Assessment, and Risk Assessment for Emerging Threats [electronic journal]. Environmental Science and Technology, 45, 12, pp. 5068–5074. [accessed on 23.8.2012]. Available at: http://pubs.acs.org/doi/abs/10.1021/es100959q

Luoma M. 2011. Työmatkaliikenteen onnettomuudet ja niihin vaikuttaminen. Master of Science Thesis. Helsinki. Aalto University - School of Engineering, Department of Civil and Environmental Engineering. 86 p. + appendices 10 p.

Mäkelä A., Pöyhönen P. 2010. Kivihiiltä idästä ja etelästä – Vastuullisuus energiayhtiöiden ostoissa [electronic report]. Helsinki, FinnWatch 3/2010. 15 p. [accessed on 23.8.2012]. Available at: http://178.79.152.176/fw/images/stories/Kivihiilta_idasta_ja_etelasta.pdf

Metso. 2011. Metso's Health, Safety and Environment Policy. [PDF]. [accessed on 12.9.2012]. Available at: http://www.metso.com/corporation/articles_eng.nsf/WebWID/WTB-120829-2256F-F8B76/$File/HSE%20policy_metso_com.pdf

Ministry of Transport and Communications. 2010. Road traffic safety. Background report for Road Safety Programme 2011-2014 [electronic report]. Helsinki, Publications of the Ministry of Transport and Communications 35/2010. 65 p. + appendices 1 p. [accessed on 23.8.2012]. Available at: http://www.lvm.fi/c/document_library/get_file?folderId=964900&name=DLFE-11090.pdf&title=Julkaisuja

Myllylä I. 2012. Vapo-viesti 2/2012: Poriin rakennetaan uutta monipolttoainevoimalaitosta. [WWW]. [accessed on 23.8.2012]. Available at: http://www.vapoviesti.fi/index.php?id=1186&selPage=16&type=2&articleId=71

Myllymaa T., Mollis K., Tohka A., Rantanen P., Ollikainen M., Dahlbo H. 2008. Jätteiden kierrätyksen ja polton käsittelyketjujen ympäristökuormitus ja kustannukset – Inventaarioraportti [electronic report]. Helsinki, Reports of the Finnish Environment Institute 28/2008. 72 p. + appendices 7 p. [accessed on 23.8.2012]. Available at: www.ymparisto.fi/download.asp?contentid=92262

National Occupational Health and Safety Commission. 1998. Work-related traumatic fatalities in Australia, 1989 to 1992 – Summary report [electronic report]. Sydney. 33 p. [accessed on 23.8.2012]. Available at: http://www.safeworkaustralia.gov.au/sites/SWA/AboutSafeWorkAustralia/WhatWeDo/Publications/Documents/59/WorkRelatedTraumaticFatalitiesAustralia1989_1992_SummaryReport_ArchivePDF.pdf

National Occupational Health and Safety Commission. 2008. Work-related traumatic injury fatalities, Australia 2005–06 [electronic report]. Sydney. 24 p. [accessed on 23.8.2012]. Available at: http://www.safeworkaustralia.gov.au/sites/SWA/AboutSafeWorkAustralia/WhatWeDo/Publications/Documents/181/WorkRelatedTraumaticInjuryFatalitiesAust2005_2006_PDF.pdf

National Occupational Health and Safety Commission. 2009a. Work-related traumatic injury fatalities, Australia 2006-07 [electronic report]. Sydney. 41 p. [accessed on 23.8.2012]. Available at: http://www.safeworkaustralia.gov.au/sites/SWA/AboutSafeWorkAustralia/WhatWeDo/Publications/Documents/180/WorkRelatedTraumaticInjuryFatalitiesAust2006_2007_PDF.pdf

National Occupational Health and Safety Commission. 2009b. Notified fatalities statistical report 2008–09 [electronic report]. Sydney. 11 p. [accessed on 23.8.2012]. Available at: http://www.safeworkaustralia.gov.au/sites/SWA/AboutSafeWorkAustralia/WhatWeDo/Publications/Documents/184/NotifiedFatalitiesStatisticalReport_2008_2009_PDF.pdf

Nygren J., Antikainen R. 2010. Use of life cycle assessment (LCA) in global companies [electronic report]. Helsinki, Reports of the Finnish Environment Institute 16/2010. 29 p. [accessed on 23.8.2012]. Available at: http://www.environment.fi/download.asp?contentid=122926&lan=en

Oulun Energia. 2004. Jätteenpolttolaitoksen tekninen kuvaus ja ympäristövaikutusselvitys ympäristölupa-hakemusta varten [electronic report]. 47 p. [accessed on 23.8.2012]. Available at: http://www.arjestaenergiaa.fi/download/895/vaikutusselvitys_finalpdf/pdf

Owens J. 1997. Life-Cycle Assessment in Relation to Risk Assessment: An Evolving Perspective. Risk Analysis, 17, 3, pp. 359-365

PE International. 2012. Documentation of LCWE data in GaBi 4 [electronic report]. Stuttgart. 15 p. [accessed on 23.8.2012]. Available at: http://www.gabi-software.com/fileadmin/Documents/lcwe.pdf

Peltola H., Aittoniemi E. 2008. Traffic safety compared to the safety of other human activities 2004–2006 [electronic report]. Helsinki, Publications of the Ministry of Transport and Communications 38/2008. 47 p. appendices 4 p. [accessed on 23.8.2012]. Available at: http://www.lvm.fi/c/document_library/get_file?folderId=57092&name=DLFE-3207.pdf&title=LVM_38/2008

Pennington D.W., Potting J., Finnveden G., Lindeijer E., Jolliet O., Rydberg T., Rebitzer G. 2004. Life Cycle Assessment – Part 2: Current Impact Assessment Practice. Environment International, 30, 5, pp. 721-739.

Pettersen J., Hertwich E. 2008. Occupational health impacts: offshore crane lifts in life cycle assessment. International Journal of Life Cycle Assessment, 13, 5, pp. 440-449

Pipatti R., Svardal P., Wagner Silva Alves J., Gao Q., López Cabrera C., Mareckova K., Oonk h., Scheehle E., Sharma C., Smith A., Yamada M., Coburn J., Pingoud K., Thorsen G., Wagner F. 2006. Solid waste disposal [electronic report]. Hayama, 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Volume 5, Waste. 40 p. [accessed on 23.8.2012]. Available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_3_Ch3_SWDS.pdf

Porin Lämpövoima Oy. 2004. Jätteen energiahyödyntäminen: ympäristövaikutusten arviointiselostus [electronic report]. 140 p. [accessed on 23.8.2012]. Available at: http://www.ymparisto.fi/default.asp?contentid=135382&lan=FI

Port of Rotterdam. 2011a. Employment per sector in Rotterdam-Rijnmond. [PDF]. [accessed on 23.8.2012]. Available at: http://www.portofrotterdam.com/SiteCollectionDocuments/employment.pdf

Port of Rotterdam. 2011b. Throughput time series. [PDF]. [accessed on 23.8.2012]. Available at: http://www.portofrotterdam.com/en/Port/port-statistics/Documents/throughput_time_series.pdf

Pöyry Forest Industry Consulting Oy. 2006. Metsäenergian tuotannon, korjuun ja käytön kustannustehokkuus sekä tukijärjestelmien vaikuttavuus päästökaupan olosuhteissa [electronic report]. Vantaa. 36 p. + appendices 11 p. [accessed on 23.8.2012]. Available at: http://www.mmm.fi/attachments/ymparisto/5iOShijmp/52A07161_Loppuraportti_090806.pdf

Rabl A., Benoist A., Dron D., Peuportier B., Spadaro J., Zoughaib A. 2007. How to Account for CO_2 Emissions from Biomass in an LCA. International Journal of Life Cycle Assessment, 12, 5, pp. 281.

Reap J., Roman F., Duncan S., Bras B. 2008. A survey of unresolved problems in life cycle assessment: Part 2: impact assessment and interpretation. International Journal of Life Cycle Assessment, 13, 5, pp. 374–388.

Rebitzer G., Ekvall T., Frischknecht R., Hunkeler D., Norris G., Rydberg T., Schmidt W.-P., Suh S., Weidema B.P., Pennington D.W. 2004. Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environment International, 60, 5, pp. 701-720.

Riikonen E., Kämäräinen M., Lappalainen J., Oksa P., Pääkkönen R., Santanen S., Saarela K., Sillanpää J. 2003. Työsuojelun perusteet. Helsinki. Työterveyslaitos.

Ronkainen N. 2012. Properties of Finnish soil types [electronic report]. Helsinki, The Finnish Environment 2/2012. 57 p. [accessed on 23.8.2012]. Available at: http://www.ymparisto.fi/download.asp?contentid=134704&lan=fi

Schmidt A., Poulsen P., Andreasen J., Fløe T., Poulsen K. 2004. The working environment in LCA, A new approach [electronic report]. Copenhagen, Guidelines from the Danish Environmental Protection Agency No. 72 2004. 53 p. + appendices 5 p. [accessed on 23.8.2012]. Available at: http://www.lca-center.dk/cms/webedit/images/cmsdoc__4/Metodeprojekt/arbejdsmilj%C3%B8-uk-vejledning.pdf

Seinäjoen Energia Oy. 2004. Syntypaikkalajitellun jätteen ja lietteen energiahyötykäyttö: ympäristövaikutusten arviointiselostuksen tiivistelmä [electronic report]. 8 p. [accessed on 23.8.2012]. Available at: http://www.seinajoki.fi/energia/lampo/.viranomaisasiakirjat.html/26779.pdf

Sorkka L., Koskela S., Seppälä J. 2005. Life cycle inventory analysis of hard coal based electricity generation [electronic report]. Helsinki, The Finnish Environment 797. 37 p. + appendices 8 p. [accessed on 23.8.2012]. Available at: http://www.ymparisto.fi/download.asp?contentid=44187

Spath P., Mann M., Kerr D. 1999. Life Cycle Assessment of Coal-fired Power Production [electronic report]. Golden, NREL/TP-570-25119. 98 p. + appendices 56 p. [accessed on 23.8.2012]. Available at: http://efile.mpsc.state.mi.us/efile/docs/16077/0065.pdf

Spielmann M., Bauer C., Dones R., Tuchschmid M. 2007. Transport Services. Dübendorf, ecoinvent report No. 14. 223 p.

Statistics Finland. 2008a. Työtapaturmat Suomessa vuonna 2006. [WWW]. [accessed on 23.8.2012]. Available at: http://www.stat.fi/til/ttap/2006/ttap_2006_2008-11-26_tie_001_fi.html

Statistics Finland. 2008b. Työtapaturmat Suomessa vuonna 2005. [WWW]. [accessed on 23.8.2012]. Available at: http://www.stat.fi/til/ttap/2005/ttap_2005_2008-04-18_tie_001_fi.html

Statistics Finland. 2008c. Liikenne 2006. [WWW]. [accessed on 23.8.2012]. Available at: http://www.stat.fi/til/litipa/2006/litipa_2006_2008-04-03_kat_001_fi.html

Statistics Finland. 2009a. Työtapaturmia 149 000 Suomessa vuonna 2007. [WWW]. [accessed on 23.8.2012]. Available at: http://www.stat.fi/til/ttap/2007/ttap_2007_2009-11-30_tie_001_fi.html

Statistics Finland. 2009b. Kuorma-autojen kuljettama tavaramäärä väheni 15 prosenttia loka-joulukuussa 2008. [WWW]. [accessed on 23.8.2012]. Available at: http://www.stat.fi/til/kttav/2008/04/kttav_2008_04_2009-02-06_kat_001.html

Statistics Finland. 2009c. Liikenne 2008. [WWW]. [accessed on 23.8.2012]. Available at: http://www.stat.fi/til/litipa/2008/litipa_2008_2009-12-30_kat_001_fi.html

Statistics Finland. 2010a. Työtapaturmia 153 000 Suomessa vuonna 2008. [WWW]. [accessed on 23.8.2012]. Available at: http://www.stat.fi/til/ttap/2008/ttap_2008_2010-11-30_tie_001_fi.html

Statistics Finland. 2010b. Kuorma-autojen tavarankuljetukset vähenivät vuonna 2009. [WWW]. [accessed on 23.8.2012]. Available at: http://www.stat.fi/til/kttav/2009/kttav_2009_2010-05-28_tie_001_fi.html

Statistics Finland. 2010c. Production of electricity and industrial heat decreased in 2009. [WWW]. [accessed on 23.8.2012]. Available at: http://www.stat.fi/til/salatuo/2009/salatuo_2009_2010-09-29_tie_001_en.html

Statistics Finland. 2011a. Työtapaturmia 128 000 Suomessa vuonna 2009. [WWW]. [accessed on 23.8.2012]. Available at: http://www.stat.fi/til/ttap/2009/ttap_2009_2011-11-30_tie_001_fi.html

Statistics Finland. 2011b. Palkansaajien työpaikkatapaturmat työkyvyttömyyden keston mukaan vuosina 1996-2009 [database]. [accessed on 23.8.2012]. Available at: http://pxweb2.stat.fi/Database/StatFin/tym/ttap/ttap_fi.asp

Statistics Finland. 2011c. Liikenne 2009. [WWW]. [accessed on 23.8.2012]. Available at: http://www.stat.fi/til/litipa/2009/litipa_2009_2011-02-22_kat_001_fi.html

Statistics Finland. 2011d. Sähkön ja lämmön tuotanto kasvoi vuonna 2010. [WWW]. [accessed on 23.8.2012]. Available at: http://www.stat.fi/til/salatuo/2010/salatuo_2010_2011-10-06_tie_001_fi.html

Statistics Finland. 2012a. Fuel classification 2011 [database]. [accessed on 23.8.2012]. Available at: http://www.stat.fi/tup/khkinv/khkaasut_polttoaineluokitus.html

Statistics Finland. 2012b. Työvoimatutkimus: Työlliset ja palkansaajat sekä työllisten ja palkansaajien tehdyt työtunnit toimialan mukaan (TOL 2008 versio 8), 15-74-vuotiaat [database]. [accessed on 23.8.2012]. Available at: http://pxweb2.stat.fi/database/StatFin/Tym/tyti/tyti_fi.asp

Sundqvist J.-O. 1999. Life cycles assessments and solid waste – Guidelines for solid waste treatment and disposal in LCA [electronic report]. Stockholm, IVL, Swedish Environmental Research Institute. 133 p. + appendices 26 p. [accessed on 2.10.2012]. Available at: http://www.naturvardsverket.net/Documents/publikationer/afr-r-279-se.pdf

Taivainen K. 2012. Maintenance manager, HelenService. Helsinki. Interview 6.8.2012.

Tanninen L. 2008. Haapaniemi 3 vähentää päästöjä ja lisää huoltovarmuutta. [WWW]. [accessed on 23.8.2012]. Available at: http://www.kuopionenergia.fi/fi/?id=36&selArticle=88

Tolle D.A., Hesse D.J., Ghadwell G.B., Cooper J.S., Evers D. P. 2001. Comparison of Two Equivalency Factor Approaches with Simplified Risk Assessment for LCIA of Toxicity Impact Potential. International Journal of Life Cycle Assessment, 6, 2, pp. 96-105.

Trozzi C., Rentz O., Oertel D., Woodfield M., Stewart R. 2010. Combustion in energy and transformation industries [electronic report]. Copenhagen, EMEP/EEA air pollutant emission inventory guidebook 2009: Technical report No 9/2009. [accessed on 23.8.2012]. Available at: http://www.eea.europa.eu/publications/emep-eea-emission-inventory-guidebook-2009/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-1-combustion-in-energy-industries-tfeip-endorsed-draft.pdf

Tsupari E., Soimakallio S., Arnold M. 2008. Yhdyskuntajätteen kahden energiahyödyntämistavan eroavuudet ilmastonmuutoksen hillinnän näkökulmasta. Espoo, VTT Tiedotteita 2446. 48 p. + appendices 5 p. [accessed on 23.8.2012]. Available at: http://www.vtt.fi/inf/pdf/tiedotteet/2008/T2446.pdf

Udo de Haes H., Jolliet O., Finnveden G., Hauschild M., Krewitt W., Müller-Wenk R. 1999a. Best Available Practice Regarding Impact Categories Category Indicators in Life

Cycle Impact Assessment - Background Document for the Second Working Group on Life Cycle Impact Assessment of SETAC-Europe (WIA-2), part 2. International Journal of Life Cycle Assessment, 4, 3, pp. 167- 174

Udo de Haes H., Jolliet O., Finnveden G., Hauschild M., Krewitt W., Müller-Wenk R. 1999b. Best Available Practice Regarding Impact Categories Category Indicators in Life Cycle Impact Assessment - Background Document for the Second Working Group on Life Cycle Impact Assessment of SETAC-Europe (WIA-2), part 1. International Journal of Life Cycle Assessment, 4, 2, pp. 66- 74

United Nations Environment Programme. 2003. Evaluation of Environmental Impacts in Life Cycle Assessment [electronic report]. Paris, United Nations Publication. 38 p. + appendices 57 p. [accessed on 23.8.2012]. Available at: http://www.unep.fr/shared/publications/pdf/3234-EvalLifeCycle.pdf

United Nations Environment Programme. 2004. Why take a life cycle approach? [PDF]. [accessed on 23.8.2012]. Available at: http://www.unep.fr/shared/publications/pdf/DTIx0585xPA-WhyLifeCycleEN.pdf

United Nations Environment Programme. 2009. Guidelines for Social Life Cycle Assessment of Products [electronic report]. Paris. 92 p. + appendices 9 p. [accessed on 23.8.2012]. Available at: http://www.unep.fr/scp/publications/details.asp?id=DTI/1164/PA

United States Environmental Protection Agency. 1995. Miscellaneous Sources: Heavy Construction Operations [electronic report]. Research Triangle Park, AP 42 Fifth Edition: Volume I. 7 p. [accessed on 23.8.2012]. Available at: http://www.epa.gov/ttn/chief/ap42/ch13/final/c13s02-3.pdf

Vakkuri R. 2011. Purkubetoni hyödynnetään, mutta vielä yksipuolisesti [electronic journal]. Betoni, 2, pp. 46-51. [accessed on 23.8.2012]. Available at: http://www.elementtisuunnittelu.fi/Download/23693/BET1102_s46-51.pdf

Vandecasteele C., Wauters G., Arickx S., Jaspers M., Van Gerven T. 2007. Integrated Municipal Solid Waste Treatment Using Grate Furnace Incienrator: The Indaver Case. Waste Management, 27, 10, pp. 1366–1375

Vantaan Energia Oy. 2007. Jätevoimalahankkeen YVA-selostus [electronic report]. 260 p. [accessed on 23.8.2012]. Available at: http://www.vantaanenergia.fi/fi/TietoaKonsernista/jatevoimalahanke/yva/Sivut/ymparistovaikutusten_arviointi.aspx

Vapo Oy. 2006. Jätteenpolttolaitos ja tuhkan läjitysalue: Ympäristövaikutusten arviointiselostus [electronic report]. 155 p. + appendices 34 p. [accessed on 23.8.2012]. Available at: http://www.ymparisto.fi/download.asp?contentid=48412&lan=fi

Vehmas A., Ojala T., Seimelä K. 2009. Heavy vehicle accidents in accident investigation reports – Risks and proposed preventative safety measures [electronic report]. Helsinki, LINTU reports 2/2009. 115 p. + appendices 16 p. [accessed on 23.8.2012]. Available at: http://www.lintu.info/RASLON.pdf

Vesanto P., Hiltunen M., Moilanen A., Kaartinen T., Laine-Ylijoki J., Sipilä K., Wilen C. 2007. Kierrätyspolttoaineiden ominaisuudet ja käyttö: Selvitys kierrätyspolttoaineiden laatuominaisuuksista ja soveltuvuudesta leijupolttoon [electronic report]. Espoo, VTT Research Notes 2416. 55 p. + appendices 4 p. [accessed on 23.8.2012]. Available at: http://www.vtt.fi/inf/pdf/tiedotteet/2007/T2416.pdf

VR Group. 2012. Vuosiraportti 2011 [electronic report]. 57 p. [accessed on 23.8.2012]. Available at: http://www.vrgroupraportti.fi/files/vr_ar2011/pdf/VRGROUP_toimintakertomus_tilinpaatos_2011.pdf

Weidema B. 2001. Avoiding Co-Product Allocation in Life-Cycle Assessment. Journal of Industrial Ecology, 4, 3, pp. 11-33.

Westenergy Oy Ab. 2008. Jätteen energiakäyttöhanke: ympäristövaikutusten arviointiselostus [electronic report]. 66 p. [accessed on 23.8.2012]. Available at: http://www.westenergy.fi/docs/westenergy_yvaselostus.pdf

Winkler J. 2005. Comparative Evaluation of Life Cycle Assessment Models for Solid Waste Management. The International Journal of Life Cycle Assessment, 10, 2, pp. 156-157.

World Health Organization. 2012a. Metrics: Disability-Adjusted Life Year (DALY) [WWW]. [accessed on 23.8.2012]. Available at: http://www.who.int/healthinfo/global_burden_disease/metrics_daly/en/

World Health Organization. 2012b. Disability weights, discounting and age weighting of DALYs [WWW]. [accessed on 23.8.2012]. Available at: http://www.who.int/healthinfo/global_burden_disease/daly_disability_weight/en/index.html

Appendix A Data used for calculating the characterization factors for accidents

Characterization factors for occupational accidents in Finland

Table A1. *Sex distribution of fatal and serious non-fatal occupational accidents (Federation of Accident Insurance Institutions 2011; Statistics Finland 2011b)*

	Fatal accidents		Serious non-fatal accidents	
	Male	Female	Male	Female
2005	45	5	40050	14359
2006	42	4	40515	14777
2007	32	5	40513	14973
2008	26	1	38732	15247
2009	22	4	29490	13508

Table A2. *Average age at the time of fatal and serious non-fatal occupational accidents (Federation of Accident Insurance Institutions 2011; Statistics Finland 2011b)*

	Fatal accidents		Serious non-fatal accidents
	Male	Female	Male and female (no separated data available)
2005	42,39	39,5	43,7
2006	43,31	42	43,5
2007	44,81	47,5	43,8
2008	45,65	39,5	44,3
2009	41,77	57	44,6

Table A3. *Average life expectancies corresponding to the average age by the time of accident in different years (Eurostat 2012d)*

	Fatal accidents		Serious non-fatal accidents	
	Male	Female	Male	Female
2005	35,5	43,5	37,3	43,5
2006	34,9	42,0	37,6	43,9
2007	30,5	36,4	37,7	44
2008	32,7	44,1	38,2	44,1
2009	36,4	28,5	37,3	43,4

Table A4. *Distribution of serious non-fatal occupational accidents resulting in given medical condition by severity (duration) (Eurostat 2012a; Eurostat 2012b; Federation of Accident Insurance Institutions 2011)*

	4 - 6d lost	7 - 13d lost	14 - 20d lost	21d - 1m lost	1 - 3m lost	3 - 6m lost	6-12m lost	Permanent disability
Total	29,24 %	33,27 %	11,69 %	8,02 %	12,34 %	3,08 %	2,03 %[3]	0,33 %[3]
Open wound not involving traumatic amputation	37,54 %[1]	37,73 %[1]	10,34 %[1]	5,93 %[1]	6,37 %[1]	1,29 %[1]	0,70 % [1;3]	0,11 %[1;3]
Superficial injury	30,88 %[1]	48,78 %[1]	9,12 %[1]	3,73 %[1]	5,75 %[1]	0,91 %[1]	0,71 %[1;3]	0,12 %[1;3]
Bone fractures	3,91 %	10,96 %	12,42 %	17,88 %	39,46 %	8,18 %	6,19 %[3]	1,01 %[3]
Dislocation	29,80 %[1]	31,88 %[1]	12,14 %[1]	9,33 %[1]	11,95 %[1]	2,93 %[1]	1,69 %[1;3]	0,28 %[1;3]
Sprains and strains of joints and adjacent muscles	29,90 %[1]	33,58 %[1]	12,59 %[1]	7,36 %[1]	10,93 %[1]	3,40 %[1]	1,92 %[1;3]	0,31 %[1;3]
Traumatic amputations	3,00 %	4,00 %	4,00 %	11,50 %	46,50 %	15,00 %	13,76 %[3]	2,24 %[3]
Intracranial injury, including concussion	44,28 %[1]	25,41 %[1]	12,24 %[1]	5,82 %[1]	7,64 %[1]	2,06 %[1]	2,19 %[1;3]	0,36 %[1;3]
Internal injury of chest, abdomen and pelvis	30,99%[1]	35,86 %[1]	11,91 %[1]	7,81 %[1]	9,21 %[1]	2,64 %[1]	1,35 %[1]	0,22 %[1;3]
Burns, scalds and frostbites	30,54 %	37,69 %	15,02 %	8,78 %	6,44 %	0,92 %	0,53 %[3]	0,09 %[3]
Poisonings and infections	22,38 %	30,77 %	17,48 %	11,19 %	13,29 %	2,80 %	1,80 %[3]	0,29 %[3]
Drownings and asphyxiations	100,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %	0,00 %[3]	0,00 %[3]
Effects of sound, vibration and pressure	44,44 %	22,22 %	11,11 %[2]	11,11 %[2]	11,11 %[2]	0,00 %[2]	0,00 %[2;3]	0,00 %[2;3]
Effects of temperature extremes, light and radiation	42,86 %	28,57 %	9,52 %[2]	4,76 %[2]	4,76 %[2]	4,76 %[2]	4,10 %[2;3]	0,67 %[2;3]
Shocks	44,00 %	37,00 %	11,00 %	4,00 %	2,00 %[2]	0,00 %[2]	1,72 %[2;3]	0,28 %[2;3]
Multiple injuries	16,58 %	24,35 %	11,92 %	11,40 %	18,13 %	6,22 %	9,80 %[3]	1,60 %[3]
Other not elsewhere mentioned	34,32 %	26,94 %	9,59 %	9,96 %	11,44 %	3,69 %	3,49 %[3]	0,57 %[3]
Unspecified	27,72 %	31,68 %	13,61 %	10,64 %	10,15 %	3,22 %	2,55 %[3]	0,42 %[3]

[1]Calculated assuming the same distribution of severities as reported for the specific medical condition in EU-15 countries in 2005-2007 (Eurostat 2012b)
[2]Estimated based on the total amount of accidents in the specific class of severity and medical condition, and the distribution of severities reported for the specific medical condition in EU-15 countries in 2005-2007 (Eurostat 2012a; Eurostat 2012b)
[3]Estimated based on Federation of Accident Insurance Institutions (2011) for the distribution of permanent injuries and injuries lasting between 6 and 12 months

Table A6. *Occupational accidents by type of injury and industry sector (including also fatal accidents due to limitations caused by statistics) (Eurostat 2012a; Eurostat 2012b; Eurostat 2012c)*

	NACE2 A	NACE2 B	NACE2 C	NACE2 D	NACE2 E	NACE2 F	NACE2 H
Total (<4d)	53,49 %[1]	53,49 %[1]	53,49 %[1]	53,49 %[1]	53,49 %[1]	53,49 %[1]	53,49 %[1]
Total (≥4d)	46,51 %	46,51 %	46,51 %	46,51 %	46,51 %	46,51 %	46,51 %
Open wound not involving traumatic amputation	7,24 %[2]	5,74 %[2]	10,05 %[2]	7,06 %[2]	5,23 %[2]	7,90 %[2]	4,66 %[2]
Superficial injury	4,64 %[2]	3,67 %[2]	6,43 %[2]	4,52 %[2]	3,35 %[2]	5,06 %[2]	2,98 %[2]
Bone fractures	7,08 %	8,03 %	4,45 %	5,90 %	5,07 %	5,49 %	4,94 %
Dislocation	2,63 %[2]	2,95 %[2]	2,06 %[2]	2,79 %[2]	3,03 %[2]	2,72 %[2]	3,26 %[2]
Sprains and strains of joints and adjacent muscles	16,08 %[2]	18,09 %[2]	12,62 %[2]	17,08 %[2]	18,54 %[2]	16,67 %[2]	19,96 %[2]
Traumatic amputations (Loss of body parts)	0,21 %	0,22 %[3]	0,32 %	0,12 %[3]	0,10 %[3]	0,23 %	0,11 %
Intracranial injury, including concussion	2,15 %[2]	1,65 %[2]	2,31 %[2]	1,92 %[2]	2,36 %[2]	1,89 %[2]	2,43 %[2]
Internal injury of chest, abdomen and pelvis	5,43 %[2]	4,17 %[2]	5,85 %[2]	4,85 %[2]	5,96 %[2]	4,77 %[2]	6,14 %[2]
Burns, scalds and frostbites	0,59 %	0,22 %[3]	1,43 %	1,31 %	0,91 %	0,66 %	0,36 %
Poisonings and infections	0,42 %	0,22 %[3]	0,15 %	0,12 %[3]	0,10 %[3]	0,18 %	0,11 %
Drownings and asphyxiations	0,00 %	0,22 %[3]	0,01 %[3]	0,12 %[3]	0,10 %[3]	0,01 %[3]	0,01 %[3]
Effects of sound, vibration and pressure	0,00 %	0,22 %[3]	0,01 %[3]	0,12 %[3]	0,10 %[3]	0,01 %[3]	0,01 %[3]
Effects of temperature extremes, light and radiation	0,00 %	0,22 %[3]	0,03 %	0,12 %[3]	0,10 %[3]	0,02 %	0,01 %[3]
Shocks	0,00 %	0,22 %[3]	0,01 %[3]	0,12 %[3]	0,10 %[3]	0,01 %[3]	0,44 %
Multiple injuries	0,04 %	0,22 %[3]	0,12 %	0,12 %[3]	0,10 %[3]	0,18 %	0,40 %
Other not elsewhere mentioned	0,29 %	0,22 %[3]	0,34 %	0,12 %[3]	1,30 %	0,27 %	0,21 %
Unspecified	0,29 %	0,22 %[3]	0,33 %	0,12 %[3]	0,10 %[3]	0,43 %	0,49 %

[1]Calculated based the distribution of accidents leading to less than four and over three days absence from work in Finland in 2005-2009 (Federation of Accident Insurance Institutions 2011)
[2]Calculated assuming the same distribution of severities as reported for the specific medical condition in EU-15 countries in 2005-2007 (Eurostat 2012b)
[3]Calculated assuming the same distribution of medical conditions as in the case of Finnish national average (Eurostat 2012a)

Characterization factors for occupational accidents in EU

Table A7. *Sex distribution of fatal and serious non-fatal occupational accidents (Eurostat 2012e)*

	Fatal accidents		Serious non-fatal accidents	
	Male	Female	Male	Female
2005	n.d	n.d	n.d	n.d
2006	n.d	n.d	n.d	n.d
2007	n.d	n.d	n.d	n.d
2008	2609	108	2323415	551518
2009	n.d	n.d	n.d	n.d

Table A8. *Average age at the time of fatal and serious non-fatal occupational accidents (Eurostat 2012e)*

	Fatal accidents		Serious non-fatal accidents	
	Male	Female	Male	Female
2005	n.d	n.d	n.d	n.d
2006	n.d	n.d	n.d	n.d
2007	n.d	n.d	n.d	n.d
2008	45,58	42,29	38,71	39,01
2009	n.d	n.d	n.d	n.d

Table A9. *Average life expectancies corresponding to the average age by the time of accident in different years (Eurostat 2012d)*

	Fatal accidents		Serious non-fatal accidents	
	Male	Female	Male	Female
2005	n.d	n.d	n.d	n.d
2006	n.d	n.d	n.d	n.d
2007	n.d	n.d	n.d	n.d
2008	32,7	42,5	40,3	45,4
2009	n.d	n.d	n.d	n.d

Characterization factors for commuting accidents in Finland

Table A10. *Sex distribution of fatal and serious non-fatal commuting accidents (Federation of Accident Insurance Institutions 2011; Statistics Finland 2008a, 2008b, 2009a, 2010a and 2011a)*

	Fatal accidents		Serious non-fatal accidents	
	Male	Female	Male	Female
2005	25	6	3354	5874
2006	10	6	3496	5854
2007	13	12	3264	5670
2008	9 (1)	9 (1)	3656	7044
2009	8	3	2943	5591

(1) Estimated based on data reported by Statistics Finland (2010a)

Table A11. *Average age at the time of fatal and serious non-fatal commuting accidents (Federation of Accident Insurance Institutions 2011)*

	Fatal accidents		Serious non-fatal accidents
	Male	Female	Male and female (no separated data available)
2005	n.d[1]	n.d[1]	43,708929
2006	n.d[1]	n.d[1]	43,480214
2007	n.d[1]	n.d[1]	43,781957
2008	n.d[1]	n.d[1]	44,324766
2009	n.d[1]	n.d[1]	44,570424

[1]The same average age as for non-fatal accidents used for later calculations

Table A12. *Average life expectancies corresponding to the average age by the time of accident in different years (Eurostat 2012d)*

	Fatal accidents		Serious non-fatal accidents	
	Male	Female	Male	Female
2005	33,7	39,7	33,7	39,7
2006	34,9	41	34,9	41
2007	34,1	40,2	34,1	40,2
2008	34,5	40,3	34,5	40,3
2009	33,7	39,5	33,7	39,5

Characterization factors for commuting accidents in EU-15

Table A13. *Average life expectancies corresponding to the average age by the time of accident in different years. Approximated based on Finnish data regarding age and sex distribution. (Eurostat 2012d)*

	Fatal accidents		Serious non-fatal accidents	
	Male	Female	Male	Female
2005	34,7	39,9	34,7	39,9
2006	35,6	41,3	35,6	41,3
2007	35,4	40,5	35,4	40,5
2008	35,6	40,6	35,6	40,6
2009	34,7	39,6	34,7	39,6

Appendix B Determination of best applicable accident frequency for background processes

Table B1. *Calculated values relative to those given in GaBi databases*

		NACE A		NACE B	
		FA	**NFA**	**FA**	**NFA**
Production of energy	Electricity from solid biomass, FI	212 %	95 %	498 %	155 %
	Electricity from wind power, FI	230 %	93 %	542 %	151 %
	Electricity from nuclear power, FI	229 %	94 %	538 %	152 %
	Electricity from hard coal, FI	171 %	100 %	403 %	162 %
	Electricity from natural gas, FI	200 %	97 %	471 %	158 %
	Electricity from fuel oil, FI	209 %	96 %	491 %	156 %
	Electricity from waste, FI	193 %	99 %	453 %	161 %
	Electricity grid mix, FI	193 %	98 %	455 %	159 %
Fuel production	Diesel, EU-27	218 %	95 %	513 %	155 %
	Light fuel oil, EU-27	221 %	95 %	519 %	154 %
	Natural gas, EU-27	231 %	94 %	544 %	152 %
Production of steel materials	Finished cold rolled steel coil, RER	43 %	154 %	100 %	250 %
	Pickled hot rolled steel coil, RER	43 %	154 %	100 %	250 %
	Steel rebar, GLO	43 %	154 %	100 %	250 %
	Welded steel pipe, GLO	43 %	154 %	100 %	250 %
	Steel scrap, GLO	43 %	154 %	100 %	250 %
Production of plastics	PE-HD granulate, DE	206 %	103 %	483 %	167 %
	PVC granulate, DE	204 %	102 %	480 %	165 %
	PS granulate, DE	224 %	105 %	526 %	171 %
Minerals production	Sand	48 %	149 %	114 %	243 %
	Limestone flour (dried), DE	176 %	108 %	414 %	176 %
	Lime, DE	175 %	115 %	411 %	186 %
	Calcium hydroxide, DE	170 %	119 %	400 %	194 %
Production of chemicals	Organic chemicals, unspecified	219 %	101 %	514 %	164 %
	Inorganic chemicals, unspecified	203 %	100 %	479 %	162 %
	Ammonia, RER	198 %	98 %	465 %	159 %
	Chlorine, DE	206 %	96 %	485 %	157 %
	Sodium hydroxide, DE	1798 %	212 %	4230 %	345 %
	Sulphuric acid, RER	216 %	95 %	509 %	154 %
	Oxygen, EU-27	182 %	100 %	428 %	162 %
Water	Process water from groundwater, RER	206 %	97 %	484 %	157 %
	Process water from surface water, RER	206 %	97 %	484 %	157 %

Table B1. *Continued*

NACE C		NACE D		NACE E		NACE F	
FA	NFA	FA	NFA	FA	NFA	FA	NFA
55 %	82 %	136 %	40 %	165 %	136 %	187 %	135 %
60 %	80 %	148 %	39 %	180 %	132 %	204 %	131 %
59 %	81 %	147 %	39 %	178 %	133 %	202 %	132 %
44 %	86 %	110 %	42 %	133 %	142 %	151 %	141 %
52 %	84 %	128 %	41 %	156 %	138 %	177 %	137 %
54 %	83 %	134 %	40 %	163 %	136 %	184 %	135 %
50 %	85 %	124 %	42 %	150 %	141 %	170 %	140 %
50 %	84 %	124 %	41 %	151 %	139 %	171 %	138 %
56 %	82 %	140 %	40 %	170 %	135 %	193 %	134 %
57 %	81 %	142 %	40 %	172 %	134 %	195 %	133 %
60 %	81 %	148 %	39 %	180 %	133 %	204 %	132 %
11 %	132 %	27 %	64 %	33 %	218 %	38 %	217 %
11 %	132 %	27 %	64 %	33 %	218 %	38 %	217 %
11 %	132 %	27 %	64 %	33 %	218 %	38 %	217 %
11 %	132 %	27 %	64 %	33 %	218 %	38 %	217 %
11 %	132 %	27 %	64 %	33 %	218 %	38 %	217 %
53 %	88 %	132 %	43 %	160 %	146 %	182 %	145 %
53 %	87 %	131 %	43 %	159 %	144 %	180 %	143 %
58 %	90 %	144 %	44 %	174 %	149 %	198 %	148 %
13 %	128 %	31 %	63 %	38 %	212 %	43 %	210 %
46 %	93 %	113 %	45 %	137 %	154 %	155 %	153 %
45 %	99 %	112 %	48 %	136 %	163 %	154 %	162 %
44 %	103 %	109 %	50 %	133 %	170 %	150 %	168 %
57 %	87 %	140 %	42 %	170 %	144 %	193 %	143 %
53 %	86 %	131 %	42 %	159 %	142 %	180 %	141 %
51 %	84 %	127 %	41 %	154 %	139 %	175 %	138 %
53 %	83 %	132 %	40 %	161 %	137 %	182 %	136 %
465 %	183 %	1153 %	89 %	1402 %	301 %	1589 %	299 %
56 %	82 %	139 %	40 %	169 %	135 %	191 %	134 %
47 %	86 %	117 %	42 %	142 %	141 %	161 %	140 %
53 %	83 %	132 %	40 %	160 %	137 %	182 %	136 %
53 %	83 %	132 %	40 %	160 %	137 %	182 %	136 %

Table B1. *Continued*

NACE H		National average		NACE A-F, H average	
FA	NFA	FA	NFA	FA	NFA
169 %	90 %	67 %	68 %	117 %	96 %
184 %	88 %	73 %	67 %	127 %	94 %
182 %	89 %	73 %	67 %	126 %	95 %
137 %	94 %	54 %	71 %	94 %	101 %
160 %	92 %	64 %	70 %	110 %	98 %
167 %	91 %	66 %	69 %	115 %	97 %
154 %	94 %	61 %	71 %	106 %	100 %
154 %	92 %	61 %	70 %	107 %	99 %
174 %	90 %	69 %	68 %	120 %	96 %
176 %	89 %	70 %	68 %	122 %	95 %
184 %	89 %	73 %	67 %	127 %	95 %
34 %	145 %	14 %	110 %	23 %	155 %
34 %	145 %	14 %	110 %	23 %	155 %
34 %	145 %	14 %	110 %	23 %	155 %
34 %	145 %	14 %	110 %	23 %	155 %
34 %	145 %	14 %	110 %	23 %	155 %
164 %	97 %	65 %	74 %	113 %	104 %
163 %	96 %	65 %	73 %	112 %	103 %
179 %	99 %	71 %	75 %	123 %	106 %
39 %	141 %	15 %	107 %	27 %	151 %
140 %	102 %	56 %	77 %	97 %	109 %
139 %	108 %	56 %	82 %	96 %	116 %
136 %	113 %	54 %	86 %	94 %	121 %
174 %	96 %	69 %	72 %	120 %	102 %
162 %	94 %	65 %	71 %	112 %	101 %
158 %	92 %	63 %	70 %	109 %	99 %
164 %	91 %	65 %	69 %	113 %	97 %
1435 %	201 %	571 %	152 %	990 %	214 %
173 %	90 %	69 %	68 %	119 %	96 %
145 %	94 %	58 %	71 %	100 %	101 %
164 %	91 %	65 %	69 %	113 %	97 %
164 %	91 %	65 %	69 %	113 %	97 %

Table B2. *t-test results for NACE A-F and H sectors, EU-15 average and NACE A-F and H average.*

	NACE A		NACE B		NACE C		NACE D	
	FA	NFA	FA	NFA	FA	NFA	FA	NFA
Average	2,57	1,06	6,05	1,72	0,67	0,91	1,65	0,44
Standard deviation	3,10	0,24	7,29	0,39	0,80	0,21	1,99	0,10
Standard error	0,60	0,05	1,40	0,08	0,15	0,04	0,38	0,02
t-value	2,63	1,20	3,60	9,49	2,17	2,28	1,70	28,61
p-value	0,01	0,24	0,00	0,00	0,04	0,03	0,10	0,00

Table B2. *Continued*

NACE E		NACE F		NACE H		EU-15 average		NACE A-F and H	
FA	NFA	FA	NFA	FA	NFA	FA	NFA	FA	NFA
2,00	1,50	2,27	1,49	2,05	1,00	0,82	0,76	1,42	1,07
2,42	0,34	2,74	0,34	2,47	0,23	0,98	0,17	1,71	0,24
0,46	0,07	0,53	0,07	0,48	0,04	0,19	0,03	0,33	0,05
2,16	7,57	2,41	7,47	2,21	0,01	0,97	7,34	1,27	1,42
0,04	0,00	0,02	0,00	0,04	0,99	0,34	0,00	0,22	0,17

Appendix C Inventory data for occupational and commuting accidents

Foreground processes

Table C1. *Accidents associated with the manufacturing of the gasification plant infrastructure*

	FA	NFA	FAC	NFAC
Pre-manufacturing of power plant components: direct accidents [pcs / gasification plant]	0 (A)	27,7 (A)	1,25E-02 (A)	11,8 (A)
Construction of gasification plant, Metso Power's and its subcontractor's employees: direct accidents [pcs / gasification plant]	5,00E-2 (SC)	2,55 (SC)	1,62E-03 (SC)	1,53 (SC)
Construction of gasification plant, other employees: direct accidents [pcs / gasification plant]	9,95E-03 (SC)	27,3 (SC)	1,33E-03 (SC)	1,22 (SC)

Table C2. *Accidents associated with the operation of the gasification plant*

Operation of the plant: direct accidents [pcs / t REF]	4,17E-09 (SC)	4,74E-06 (SC)	5,92E-10 (SC)	7,59E-07 (SC)

Table C3. *Accidents associated with the deconstruction of the gasification plant infrastructure*

Emptying of the equipment: direct accidents [pcs / gasification plant]	3,16E-04 (SC)	0,360 (SC)	4,50E-05 (SC)	5,76E-02 (SC)
Deconstruction of the plant: direct accidents [pcs / gasification plant]	6,34E-04 (SC)	1,74 (SC)	8,48E-05 (SC)	7,80E-02 (SC)

Background processes

Table C4. *Accidents associated with transportation processes*

Road transportations, Finland (short and long distance): direct accidents [pcs / tkm]	1,25E-10 (SC)	2,06E-07 (SC)	1,91E-11 (SC)	1,76E-08 (SC)
Road transportations, EU-15 (short and long distance): direct accidents [pcs / tkm]	1,48E-10 (SC)	1,20E-07 (SC)	3,10E-11 (SC)	1,56E-08 (SC)
Road transportations, Finland/EU-15, short distance: indirect accidents [pcs / tkm]	1,45E-11 (SC)	2,28E-08 (SC)	5,29E-12 (SC)	2,66E-09 (SC)
Road transportations, Finland/EU-15, long distance: indirect accidents [pcs / tkm]	9,36E-12 (SC)	1,47E-8 (SC)	3,42E-12 (SC)	1,72E-09 (SC)
Rail transportations, Finland: direct and indirect accidents [pcs / tkm]	3,61E-12 (SC)	4,66E-09 (SC)	6,93E-13 (SC)	6,51E-10 (SC)
Rail transportations, EU-15: direct and indirect accidents [pcs / tkm]	3,53E-12 (SC)	4,78E-9 (SC)	7,04E-13 (SC)	6,62E-10 (SC)
Water transportations: direct accidents [pcs / tkm][1]	7,30E-13 (A)	1,894E-10 (A)	1,90E-13 (A)	9,57E-11 (A)
Water transportations: indirect accidents: fuel production for vessesl [pcs / tkm]	9,63E-15 (A)	1,54E-09 (A)	3,55E-13 (A)	1,79E-10 (A)
Water transportations: indirect accidents: operations at harbor [pcs / tkm]	1,19E-12 (A)	9,67E-10 (A)	2,49E-13 (A)	1,25E-10 (A)
Water transportations: indirect accidents: energy production for harbors [pcs / tkm]	3,29E-13 (A)	4,1E-10 (A)	9,92E-14 (A)	4,99E-11 (A)

[1]Estimated based on Danish data

Table C5. *Accidents associated with the production of energy*

Energy from peat, acquisition and production of peat: direct accidents [pcs / MWh fuel]	4,20E-09 (SC)	5,08E-06 (SC)	8,12E-10 (SC)	7,63E-07 (SC)
Energy from peat, acquisition and production of peat: indirect accidents [pcs / MWh fuel]	3,98E-09 (SC)	5,00E-06 (SC)	1,21E-09 (SC)	6,08E-07 (SC)
Energy from peat, use of peat: direct accidents [pcs / MWh fuel]	2,05E-09 (SC)	2,34E-06 (SC)	2,92E-10 (SC)	3,74E-07 (SC)

Energy from peat, use of peat: indirect accidents [pcs / MWh fuel]	4,48E-09 (SC)	5,63E-06 (SC)	1,36E-09 (SC)	6,84E-07 (SC)
Energy from wood based fuels, acquisition and production of wood: direct accidents [pcs / MWh fuel]	1,13E-08 (SC)	1,08E-05 (SC)	7,14E-10 (SC)	6,29E-07 (SC)
Energy from wood based fuels, acquisition and production of wood: indirect accidents [pcs / MWh fuel]	3,10E-09 (SC)	3,90E-06 (SC)	9,42E-10 (SC)	4,74E-07 (SC)
Energy from wood based fuels, use of wood: direct accidents [pcs / MWh fuel]	2,05E-09 (A)	2,34E-06 (A)	2,92E-10 (A)	3,74E-07 (A)
Energy from wood based fuels, use of wood: indirect accidents [pcs / MWh fuel]	4,48E-09 (A)	5,63E-06 (A)	1,36E-09 (A)	6,84E-07 (A)
Production of usable district heat, average heat mix: direct and indirect accidents [pcs / MWh heat]	9,62E-08 (SC)	1,28E-04 (SC)	3,02E-08 (SC)	3,02E-08 (SC)

Table C6. *Accidents associated with the production of given materials*

Unspecified organic chemicals: direct and indirect accidents [pcs / kg]	7,69E-10 (SC)	1,14E-06 (SC)	2,81E-10 (SC)	1,41E-07 (SC)
Unspecified inorganic chemicals: direct and indirect accidents [pcs / kg]	2,71E-10 (SC)	3,85E-07 (SC)	9,75E-11 (SC)	4,90E-08 (SC)
Unspecified organic solvents: direct and indirect accidents [pcs / kg]	5,98E-10 (SC)	1,27E-06 (SC)	3,41E-10 (SC)	1,71E-07 (SC)
Concrete: direct and indirect accidents [pcs / kg]	9,10E-11 (L)	1,14E-07 (SC)	2,76E-11 (SC)	1,39E-08 (SC)
Cement: direct accidents [pcs / kg]	7,93E-12 (SC)	9,97E-09 (SC)	2,41E-12 (SC)	1,21E-09 (SC)

Table C7. *Accidents associated with generic waste management processes*

MSWI: direct accidents [pcs / t waste]	4,43E-09 (L)	5,58E-06 (L)	1,35E-09 (L)	6,77E-07 (L)
MSWI: indirect accidents [pcs / t waste]	2,36E-08 (L)	3,08E-05 (L)	1,16E-08 (L)	4,20E-06 (L)
HWI: direct accidents [pcs / t waste]	4,43E-09 (L)	5,58E-06 (L)	1,35E-09 (L)	6,77E-07 (L)
HWI: indirect accidents [pcs / t waste]	1,19E-07 (L)	2,07E-04 (L)	1,53E-07 (L)	2,95E-05 (L)

Table C8. *Accidents associated with the production of REF*

Production of REF: direct accidents [pcs / t REF]	4,30E-09 (SC)	3,18E-05 (SC)	3,54E-09 (SC)	3,33E-06 (SC)

Replaced sources of energy

Table C9. *Accidents associated with the manufacturing of hard coal power plant infrastructure*

Pre-manufacturing of power plant components: direct accidents [pcs / power plant]	0 (A)	139,1 (A)	6,31E-02 (A)	59,3 (A)
Construction of power plant, workers involved in installation of power plant equipments: direct accidents [pcs / power plant]	1,59E-03 (SC)	11,7 (SC)	1,31E-03 (SC)	1,23 (SC)
Construction of power plant, other workers: direct accidents [pcs / power plant]	7,99E-03 (SC)	22,0 (SC)	1,07E-03 (SC)	0,983 (SC)

Table C10. *Accidents associated with the mining, processing and transportation of hard coal*

Mining of hard coal: direct accidents [pcs / MWH fuel]	7,23E-08 (SC)	3,42E-05 (SC)	5,14E-09 (SC)	2,58E-06 (SC)
Mining of hard coal: indirect accidents [pcs / MWH fuel]	1,46E-08 (SC)	1,84E-05 (SC)	4,44E-09 (SC)	2,23E-06 (SC)
Transportation of hard coal: direct and indirect accidents [pcs / MWH fuel][2]	3,05E-9 (SC)	4,13E-06 (SC)	9,84E-10 (SC)	4,94E-07 (SC)

[2]Adjusted for Russian accident frequency. Not in line with generic transportation processes.

Table C11. *Accidents associated with the operation of a hard coal power plant*

Operation of the plant: direct accidents [pcs / MWH fuel]	1,31E-09 (PC)	1,64E-06 (PC)	3,97E-10 (PC)	2,00E-07 (PC)

Table C12. *Accidents associated with the deconstruction of a hard coal power plant*

Emptying of the equipment: direct accidents [pcs / gasification plant]	9,15E-04 (SC)	1,04 (SC)	1,30E-04 (SC)	0,167 (SC)

Appendix D LCI data for the premanufacturing of power plant components

AVAILABLE FOR METSO'S INTERNAL USE ONLY

Appendix E Product system model

AVAILABLE FOR METSO'S INTERNAL USE ONLY

Appendix F LCIA results

Table F1. *Occupational health impacts at category midpoints, scenarios A and B*

	M1	M2	M3	U1	U2	U3	U4
FA, Finland	1,11E-10	0	9,59E-09	1,78E-08	4,17E-09	4,58E-09	2,01E-09
FA, EU-15	3,25E-09	0	0	7,70E-09	0	7,95E-09	3,01E-08
NFA, NACE2 A, Finland	4,90E-09	0	0	1,96E-08	0	0	3,94E-11
NFA, NACE2 B, Finland	4,47E-09	0	0	1,79E-08	0	0	3,59E-11
NFA, NACE2 C, Finland	2,50E-11	4,43E-06	4,08E-07	3,18E-05	0	0	6,90E-07
NFA, NACE2 D, Finland	2,86E-09	0	0	1,15E-08	4,74E-06	0	2,30E-11
NFA, NACE2 E, Finland	0	0	0	0	0	0	0
NFA, NACE2 F, Finland	0	0	4,37E-06	0	0	0	0
NFA, NACE2 H, Finland	1,64E-07	0	0	2,22E-05	0	7,55E-06	3,15E-06
NFA, NACE2 A-F and H, EU-15	4,39E-06	0	0	1,06E-05	0	1,01E-05	4,37E-05
NFA, NACE2 A, EU-15	0	0	0	0	0	0	0
NFA, NACE2 B, EU-15	2,69E-09	0	0	0	0	0	4,79E-07
NFA, NACE2 C, EU-15	0	0	0	0	0	0	0
NFA, NACE2 D, EU-15	6,02E-10	0	0	0	0	0	0
NFA, NACE2 E, EU-15	0	0	0	0	0	0	0
NFA, NACE2 F, EU-15	0	0	0	0	0	0	0
NFA, NACE2 H, EU-15	6,97E-09	0	0	0	0	0	0
FCA, Finland	1,14E-10	2,00E-09	4,72E-10	5,99E-09	5,92E-10	7,05E-10	3,74E-10
FCA, EU-15	9,38E-10	0	0	7,20E-10	0	2,57E-09	1,04E-08
NFCA, Finland	1,73E-08	1,88E-06	4,40E-07	5,24E-06	7,59E-07	6,50E-07	3,45E-07
NFCA, EU-15	5,20E-07	0	0	5,58E-07	0	1,29E-06	5,22E-06

Table F1. *Continued*

	E1	E2	E3	R1
FA, Finland	1,66E-10	5,06E-11	1,01E-10	-2,82E-08
FA, EU-15	-2,67E-10	0	1,33E-11	-3,46E-07
NFA, NACE2 A, Finland	0	0	0	-2,64E-09
NFA, NACE2 B, Finland	0	0	0	-2,41E-09
NFA, NACE2 C, Finland	0	0	0	-2,67E-06
NFA, NACE2 D, Finland	5,76E-08	5,76E-08	0	-3,19E-05
NFA, NACE2 E, Finland	0	0	0	0
NFA, NACE2 F, Finland	2,78E-07	0	2,78E-07	-4,20E-07
NFA, NACE2 H, Finland	2,04E-08	0	0	-1,71E-07
NFA, NACE2 A-F and H, EU-15	-2,52E-08	0	2,09E-08	-9,38E-05
NFA, NACE2 A, EU-15	0	0	0	0
NFA, NACE2 B, EU-15	0	0	0	-1,30E-04
NFA, NACE2 C, EU-15	0	0	0	0
NFA, NACE2 D, EU-15	0	0	0	-4,70E-11
NFA, NACE2 E, EU-15	0	0	0	0
NFA, NACE2 F, EU-15	0	0	0	0
NFA, NACE2 H, EU-15	0	0	0	-2,20E-09
FCA, Finland	2,29E-11	7,20E-12	1,36E-11	-5,20E-09
FCA, EU-15	-1,43E-11	0	4,86E-12	-4,20E-08
NFCA, Finland	2,37E-08	9,22E-09	1,25E-08	-6,20E-06
NFCA, EU-15	-7,23E-09	0	2,44E-09	-2,11E-05

Table F2. *Occupational health impacts at category endpoint, scenarios A and B*

	M1	M2	M3	U1	U2	U3	U4
FA, Finland	4,29E-09	0	3,72E-07	6,91E-07	1,62E-07	1,78E-07	7,78E-08
FA, EU-15	1,08E-07	0	0	2,55E-07	0	2,63E-07	9,98E-07
NFA, NACE2 A, Finland	0	0	0	0	0	0	0
NFA, NACE2 B, Finland	1,68E-10	0	0	6,70E-10	0	0	1,35E-12
NFA, NACE2 C, Finland	1,58E-10	0	0	6,33E-10	0	0	1,27E-12
NFA, NACE2 D, Finland	9,92E-13	1,76E-07	1,62E-08	1,26E-06	0	0	2,74E-08
NFA, NACE2 E, Finland	7,31E-11	0	0	2,92E-10	1,21E-07	0	5,86E-13
NFA, NACE2 F, Finland	0	0	0	0	0	0	0
NFA, NACE2 H, Finland	0	0	1,45E-07	0	0	0	0
NFA, NACE2 A-F and H, EU-15	4,16E-09	0	0	5,63E-07	0	1,92E-07	8,00E-08
NFA, NACE2 A, EU-15	1,55E-07	0	0	3,75E-07	0	3,57E-07	1,54E-06
NFA, NACE2 B, EU-15	0	0	0	0	0	0	0
NFA, NACE2 C, EU-15	1,01E-10	0	0	0	0	0	1,81E-08
NFA, NACE2 D, EU-15	0	0	0	0	0	0	0
NFA, NACE2 E, EU-15	1,05E-11	0	0	0	0	0	0
NFA, NACE2 F, EU-15	0	0	0	0	0	0	0
NFA, NACE2 H, EU-15	0	0	0	0	0	0	0
FCA, Finland	1,59E-10	0	0	0	0	0	0
FCA, EU-15	4,49E-09	7,87E-08	1,85E-08	2,35E-07	2,33E-08	2,77E-08	1,47E-08
NFCA, Finland	3,48E-08	0	0	2,67E-08	0	9,52E-08	3,86E-07
NFCA, EU-15	4,16E-10	4,52E-08	1,06E-08	1,26E-07	1,82E-08	1,56E-08	8,29E-09

Table F2. *Continued*

	E1	E2	E3	R1
FA, Finland	6,43E-09	1,96E-09	3,94E-09	-1,09E-06
FA, EU-15	-8,82E-09	0	4,39E-10	-1,15E-05
NFA, NACE2 A, Finland	0	0	0	0
NFA, NACE2 B, Finland	0	0	0	-9,03E-11
NFA, NACE2 C, Finland	0	0	0	-8,52E-11
NFA, NACE2 D, Finland	0	0	0	-1,06E-07
NFA, NACE2 E, Finland	1,47E-09	1,47E-09	0	-8,13E-07
NFA, NACE2 F, Finland	0	0	0	0
NFA, NACE2 H, Finland	9,27E-09	0	9,27E-09	-1,40E-08
NFA, NACE2 A-F and H, EU-15	5,17E-10	0	0	-4,33E-09
NFA, NACE2 A, EU-15	-8,91E-10	0	7,38E-10	-3,31E-06
NFA, NACE2 B, EU-15	0	0	0	0
NFA, NACE2 C, EU-15	0	0	0	-4,89E-06
NFA, NACE2 D, EU-15	0	0	0	0
NFA, NACE2 E, EU-15	0	0	0	-8,17E-13
NFA, NACE2 F, EU-15	0	0	0	0
NFA, NACE2 H, EU-15	0	0	0	0
FCA, Finland	0	0	0	-5,03E-11
FCA, EU-15	9,02E-10	2,83E-10	5,33E-10	-2,05E-07
NFCA, Finland	-5,31E-10	0	1,80E-10	-1,56E-06
NFCA, EU-15	5,69E-10	2,21E-10	3,00E-10	-1,49E-07

Table F3. *Environmental health impacts at category endpoint, scenarios A and B*

	M1	M2	M3	U1	U2	U3	U4
Minimum emissions to air, inf. time frame	6,34E-06	1,99E-07	2,18E-06	2,92E-05	1,80E-04	4,98E-05	4,32E-05
Maximum emissions to air, inf. time frame	6,34E-06	1,99E-07	2,18E-06	2,92E-05	5,02E-04	4,98E-05	4,32E-05
Minimum emissions to air, 100a time frame	6,34E-06	1,99E-07	2,18E-06	2,92E-05	1,80E-04	4,98E-05	4,27E-05
Maximum emissions to air, 100a time frame	6,34E-06	1,99E-07	2,18E-06	2,92E-05	5,02E-04	4,98E-05	4,27E-05

Table F3. *Continued*

	E1	E2	E3	R1
Minimum emissions to air, inf. time frame	0	2,47E-07	-1,09E-06	-9,08E-04
Maximum emissions to air, inf. time frame	0	2,47E-07	-1,09E-06	-9,08E-04
Minimum emissions to air, 100a time frame	0	2,47E-07	-1,09E-06	-9,07E-04
Maximum emissions to air, 100a time frame	0	2,47E-07	-1,09E-06	-9,07E-04

Appendix G Impacts on bystanders' health

Table G1. *Impacts on bystanders' health: workplace bystanders*

Process group	Fatal accidents, unweighted	Non-fatal accidents, unweighted	Fatal accidents, weighted	Non-fatal accidents, weighted
M1	1,23E-11	3,69E-09	5,64E-10	1,30E-10
M2	4,83E-12	1,45E-09	2,21E-10	5,11E-11
M3	0	0	0	0
U1	1,19E-11	3,57E-09	5,45E-10	1,26E-10
U2	2,35E-11	7,06E-09	1,08E-09	2,49E-10
U3	7,96E-12	2,39E-09	3,64E-10	8,42E-11
U4	3,52E-11	1,06E-08	1,61E-09	3,73E-10
E1	4,46E-13	1,34E-10	2,04E-11	4,72E-12
E2	2,86E-13	8,58E-11	1,31E-11	3,03E-12
E3	1,96E-13	5,89E-11	9,00E-12	2,08E-12
R1	-4,39E-10	-1,32E-07	-2,01E-08	-4,65E-09

Table G2. *Impacts on bystanders' health: road bystanders due to transportation activities*

Process group	Fatal accidents, unweighted	Non-fatal accidents, unweighted	Fatal accidents, weighted	Non-fatal accidents, weighted
M1	4,72E-09	2,26E-07	1,74E-07	5,43E-09
M2	4,72E-09	2,26E-07	1,74E-07	5,43E-09
M3	0	0	0	0
U1	4,09E-07	2,22E-05	1,51E-05	5,32E-07
U2	0	0	0	0
U3	1,44E-07	7,58E-06	5,31E-06	1,82E-07
U4	6,61E-08	1,07E-06	2,43E-06	2,58E-08
E1	3,76E-10	2,04E-08	1,38E-08	4,88E-10
E2	0	0	0	0
E3	0	0	0	0
R1	-9,78E-07	-5,68E-06	-3,60E-05	-1,36E-07

Table G3. *Impacts on bystanders' health: road bystanders due to commuting activities*

Process group	Fatal accidents, unweighted	Non-fatal accidents, unweighted	Fatal accidents, weighted	Non-fatal accidents, weighted
M1	1,57E-09	n.d	1,30E-10	n.d
M2	8,99E-10	n.d	5,11E-11	n.d
M3	5,43E-10	n.d	0	n.d
U1	1,82E-09	n.d	1,26E-10	n.d
U2	1,61E-10	n.d	2,49E-10	n.d
U3	8,86E-10	n.d	8,42E-11	n.d
U4	2,92E-09	n.d	3,73E-10	n.d
E1	2,34E-12	n.d	4,72E-12	n.d
E2	1,95E-12	n.d	3,03E-12	n.d
E3	4,99E-12	n.d	2,08E-12	n.d
R1	-1,28E-08	n.d	-4,65E-09	n.d